IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Synthesis of Zinc(II), Mercury(II), And Iron(III) Complexes, Their Characterization Techniques And Applications

[1]Rohin Kumar Parewa, Himani Yadav, Ajay Kumar Saini, [2]Shuchi Dadheech
Research Scholar, [2]Research Scholar
[1]Department of Chemistry, Mohanlal Sukhadiya University, Udaipur-(Raj.), India.
[2]Department of Zoology, Mohanlal Sukhadiya University, Udaipur-(Raj.), India.

Abstract:
The synthesis and characterization of Zinc(II), Mercury(II), and Iron(III) complexes have garnered significant interest due to their diverse applications in fields such as catalysis, medicine, and materials science. This study focuses on the preparation of these metal complexes using various ligands, particularly Schiff bases, which exhibit chelating properties that enhance metal coordination. The complexes are synthesized through direct reaction methods involving metal salts and ligands in suitable solvents, followed by purification techniques such as recrystallization. Characterization of the synthesized complexes is achieved through an array of analytical techniques. UV-Visible spectroscopy provides insights into the electronic transitions and ligand field interactions, while Infrared (IR) spectroscopy elucidates the coordination modes by identifying shifts in functional group vibrations. Nuclear Magnetic Resonance (NMR) spectroscopy reveals the electronic environments of the ligands in the complexes, enhancing our understanding of their structure. Furthermore, Single-Crystal X-ray Diffraction (SCXRD) is employed to ascertain the three-dimensional arrangements of atoms, confirming the geometries and bonding environments of the complexes. The thermal stability of the complexes is evaluated using Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC), providing essential data on their thermal behavior. Additionally, Mass Spectrometry and Cyclic Voltammetry (CV) are utilized to determine molecular weights and investigate electrochemical properties, respectively. The applications of Zinc(II), Mercury(II), and Iron(III) complexes are diverse. Zinc complexes demonstrate antimicrobial properties, making them suitable for medical applications, while Mercury complexes are explored for their catalytic abilities. Iron(III) complexes are significant in various biochemical processes and serve as potential therapeutic agents. This review provides a comprehensive overview of the synthesis, structural characterization, and application potential of Zinc(II), Mercury(II), and Iron(III) complexes. By shedding light on their properties and versatile applications, this study underscores the potential of these complexes in the development of new functional materials and therapeutic agents, paving the way for future innovations in materials science and medicinal chemistry.

Keywords: Zinc(II) complexes, Mercury(II) complexes, Iron(III) complexes, Synthesis, Characterization, Schiff bases, Chelating properties, UV-Visible spectroscopy, Infrared (IR) spectroscopy.

I. INTRODUCTION

Transition metal complexes have been a significant area of research due to their wide-ranging applications in various scientific fields such as chemistry, medicine, catalysis, and materials science. Among these, the complexes of Zinc(II), Mercury(II), and Iron(III) are particularly notable for their distinctive properties and versatile coordination chemistry. The coordination of these metals with suitable ligands, such as Schiff bases, yields complexes with unique chemical behaviors, making them valuable in both fundamental research and practical applications.[1]

Metal-ligand coordination chemistry plays a crucial role in understanding the behavior of metal complexes across different environments. The formation of metal complexes involves the interaction of ligands, which donate electron pairs to the metal center, resulting in a stable structure with novel chemical and physical properties. Schiff bases, formed by the condensation of primary amines with aldehydes or ketones, are commonly employed as ligands in coordination chemistry. Their chelating ability, which stems from the presence of nitrogen and oxygen donor atoms, facilitates the formation of strong metal-ligand bonds, making them ideal for synthesizing complexes with Zinc(II), Mercury(II), and Iron(III).[2]

Schiff base ligands are particularly versatile, as their electronic and steric properties can be fine-tuned by modifying their molecular structures. This tunability directly impacts the reactivity, stability, and solubility of the metal complexes they form. The ability to manipulate the ligand framework is especially beneficial in catalysis, where optimizing the ligand structure can significantly enhance the activity of the metal complex for specific reactions.[3]

The synthesis of metal complexes, particularly those involving Zinc(II), Mercury(II), and Iron(III), has been a significant area of interest in coordination chemistry due to their wide-ranging applications in catalysis, medicinal chemistry, materials science, and biochemistry. Schiff bases, which serve as versatile ligands in these metal complexes, play an essential role due to their structural flexibility, strong chelating abilities, and ease of synthesis. Typically formed through the condensation of primary amines with aldehydes or ketones, Schiff bases contain imine (C=N) functional groups, which facilitate the coordination to transition metals. This coordination often leads to the formation of metal complexes with intriguing chemical, physical, and biological properties.[4]

Schiff bases have gained popularity in coordination chemistry due to their ability to act as bidentate or multidentate ligands, coordinating with metal ions through donor atoms such as nitrogen, oxygen, or sulfur. This chelating property is especially useful for stabilizing metal ions in different oxidation states. The ability of Schiff bases to form stable five- or six-membered chelate rings with metal ions further enhances the stability of the resulting complexes. Additionally, Schiff bases offer the flexibility to be synthesized with a wide variety of substituents on both the amine and aldehyde or ketone components, allowing fine-tuning of their electronic and steric properties. This adaptability is an advantage in the design of metal complexes for specific applications, as it enables the ligand to influence the metal's reactivity, stability, and solubility.[5]

The coordination chemistry of Schiff bases with Zinc(II), Mercury(II), and Iron(III) is of particular importance since these metal ions play vital roles in biological, environmental, and industrial processes. Each metal ion interacts differently with Schiff base ligands, leading to diverse applications for the resulting complexes. Zinc(II) is a d^{10} metal ion, meaning its d-orbitals are fully occupied, and it does not exhibit ligand field stabilization energy (LFSE). This gives Zinc(II) complexes flexibility in their coordination geometries, allowing them to adopt tetrahedral, square planar, or octahedral structures depending on the ligand and reaction conditions. Zinc(II) is also biologically essential and non-toxic, making its complexes highly desirable for use in medicinal chemistry, especially for antimicrobial and anticancer applications.[6]

The synthesis of Zinc(II) Schiff base complexes is straightforward and typically involves dissolving a Zinc(II) salt such as zinc acetate or zinc chloride in a solvent like methanol, ethanol, or acetonitrile. The Schiff base ligand is then added to the solution, and the reaction mixture is heated to facilitate complex formation. The appearance of a color change in the solution often indicates the formation of the complex. The reaction is usually complete after stirring for several hours at elevated temperatures, typically between 50-80°C. The resulting complex can be purified by recrystallization using solvents like ethanol or methanol, or by evaporating the solvent and washing the solid product with non-polar solvents like diethyl ether or hexane to remove any unreacted ligand. In some cases, Zinc(II) complexes can be prepared at room temperature, but higher temperatures are commonly used to expedite the reaction.[7] The coordination number of Zinc(II) in these complexes, whether four or six, is influenced by the steric and electronic properties of the Schiff base ligand. Bulky Schiff bases tend to favor tetrahedral Zinc(II) complexes, while less sterically hindered ligands can lead to octahedral complexes.

Mercury(II) complexes have been extensively studied for their interesting chemical properties, despite the toxic nature of mercury. Mercury(II), like Zinc(II), is a d10 metal ion and typically prefers linear or slightly distorted coordination geometries, especially in complexes with bidentate ligands such as Schiff bases. The flexibility of Mercury(II) in its coordination environment is similar to that of Zinc(II), as it does not exhibit LFSE. The synthesis of Mercury(II) Schiff base complexes is quite similar to that of Zinc(II) complexes, where a Mercury(II) salt, such as mercury(II) chloride or mercury(II) acetate, is dissolved in a polar solvent like methanol or ethanol, followed by the addition of the Schiff base ligand.[8] The mixture is usually heated to 60-80°C to promote complex formation. Mercury(II) tends to form complexes with a coordination number of two, though higher coordination numbers are possible depending on the ligand and the reaction conditions.

After the reaction, the complex is typically isolated through solvent evaporation or recrystallization. Given the environmental and health risks associated with mercury, careful handling and disposal of these complexes are essential. Researchers are also increasingly interested in developing environmentally friendly methods for synthesizing Mercury(II) complexes, including the use of greener solvents and recyclable catalysts.

Iron(III) is a d5 metal ion and generally forms octahedral complexes with Schiff bases due to its preference for a coordination number of six. Iron(III) plays a crucial role in biological systems, particularly in oxygen transport, electron transfer, and enzymatic catalysis.[9]The redox properties of Iron(III), which can undergo reversible reduction to Iron(II), make its complexes particularly attractive for applications in redox catalysis, electrochemistry, and medicinal chemistry. The synthesis of Iron(III) Schiff base complexes typically involves the reaction of iron(III) chloride or iron(III) nitrate with a Schiff base ligand in a polar solvent such as ethanol, methanol, or acetonitrile. The reaction is generally carried out under reflux conditions at 60-80°C for several hours to allow the ligand to fully coordinate with the iron center. Iron(III) complexes are often highly colored, and the formation of the complex is indicated by changes in the color of the solution. The purification of Iron(III) complexes is usually achieved through recrystallization, though solvent evaporation and filtration may also be used depending on the solubility of the complex in various solvents.[10] In some cases, a reducing agent may be necessary to obtain Iron(II) complexes, as Iron(III) complexes can be relatively inert in certain reactions. The choice of Schiff base ligand is crucial in determining the redox behavior of the complex, as different ligands can stabilize either the Iron(III) or Iron(II) oxidation state based on their electronic properties.

The success of metal complex synthesis using Schiff bases depends heavily on the choice of solvent and reaction conditions. Polar solvents like ethanol, methanol, and acetonitrile are commonly employed due to their ability to dissolve both the metal salts and Schiff base ligands, as well as their efficiency in heat transfer during refluxing. Non-polar solvents such as chloroform or dichloromethane may also be used in some cases, particularly if the metal complex is poorly soluble in polar solvents, although these are less common due to their environmental impact.[11] The reaction temperature and duration also play important roles, with some complexes forming at room temperature, while others require heating to drive the reaction to completion. Refluxing at 60-80°C is often sufficient to achieve complete complexation of the metal ion with the Schiff base ligand. Additionally, the pH of the reaction medium can influence complex formation, especially for ligands that contain protonatable groups like hydroxyl or carboxyl moieties. Adjusting the pH with weak acids or bases can improve the solubility of the ligand or the metal salt, leading to more efficient complexation.

Once the metal complex is synthesized, purification is necessary to remove unreacted metal salts, ligands, and other impurities. Recrystallization is the most commonly used purification method, as it allows for the isolation of pure, crystalline complexes that can be characterized by various analytical techniques. Solvent evaporation is another method, particularly for complexes with low solubility in the reaction solvent. Chromatography is less common but can be employed when necessary.[12] The characterization of metal complexes typically involves techniques such as UV-Visible spectroscopy, IR spectroscopy, NMR spectroscopy, mass spectrometry, and X-ray crystallography, which help confirm the structure and properties of the complexes. Thermal analysis methods such as thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) can also provide insights into the thermal stability and decomposition behavior of the complexes.

To thoroughly understand the structure and properties of these synthesized metal complexes, a combination of analytical techniques is employed.[13] UV-Visible spectroscopy offers insights into the electronic transitions within the complexes, enabling the determination of ligand field interactions and metal-to-ligand charge transfer processes. Infrared (IR) spectroscopy is used to identify the functional groups present in the ligands and to determine their coordination modes by analyzing shifts in vibrational frequencies. Nuclear Magnetic Resonance (NMR) spectroscopy provides valuable information about the electronic environment of the ligands in the metal complexes, offering insights into the bonding nature and overall structure of the complex. Single-Crystal X-ray Diffraction (SCXRD) is the most definitive technique for determining the three-dimensional arrangement of atoms within the complex, allowing for the precise measurement of bond lengths, angles, and coordination geometries. Thermal analysis techniques, such as Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC), assess the thermal stability of the metal complexes, providing data on decomposition temperatures and phase transitions. This information is crucial for understanding the stability of the complexes and their potential applications in high-temperature processes. Finally, mass spectrometry is employed to determine the molecular weight of the complexes, while cyclic voltammetry provides insights into their electrochemical properties, such as redox behavior and electron transfer kinetics.[14]

Zinc(II) complexes, for example, are biologically essential, playing a key role in various enzymatic processes. In coordination chemistry, Zinc(II) complexes have been widely studied for their antimicrobial, anticancer, and anti-inflammatory properties, making them strong candidates for drug development. Complexes of Zinc(II) with Schiff bases exhibit notable biological activity, including antibacterial and antifungal effects, which are attributed to the interactions between these complexes and biological molecules like DNA, proteins, and enzymes. In addition to their biomedical applications, Zinc(II) complexes are valuable in catalysis, particularly in organic transformations and polymerization reactions. The Lewis acidic nature of Zinc(II) ions allows them to activate substrates, facilitating reactions such as transesterification, aldol condensations, and carbon-carbon bond formation. The catalytic efficiency of these complexes can be further optimized by selecting Schiff base ligands with suitable electronic and steric characteristics.[15]

Mercury(II) complexes, despite the inherent toxicity of mercury, have been explored for their catalytic properties, particularly in reactions requiring high electrophilicity. When coordinated with Schiff bases, Mercury(II) complexes exhibit unique reactivity that can be leveraged in organic synthesis. For instance, Mercury(II) Schiff base complexes have been employed in the catalytic cyclization of alkynes and alkenes, as well as in carbonylation reactions. However, the environmental impact of Mercury(II) complexes is a significant concern. Mercury's toxicity and potential for bioaccumulation present challenges to their practical application. Consequently, current research focuses on developing more environmentally friendly catalysts and addressing the harmful effects of mercury. This includes the exploration of recyclable catalysts and the application of green chemistry principles to minimize mercury waste in industrial processes.[16]

Iron(III) complexes are another area of interest due to iron's critical role in biological systems. Iron plays a fundamental part in oxygen transport, electron transfer, and enzymatic catalysis. Iron(III) complexes, in particular, are involved in various biochemical processes, including gene expression regulation, cellular respiration, and oxidative stress responses. Iron(III)'s ability to undergo redox cycling between its Fe(III) and Fe(II) states makes it an attractive candidate for applications in medicine and biochemistry.[17] Schiff base complexes of Iron(III) have drawn significant attention for their potential therapeutic applications, particularly in treating diseases related to iron homeostasis. For example, Iron(III) Schiff base complexes have been explored as anti-cancer agents, given their ability to induce oxidative stress in cancer cells. Additionally, these complexes have been investigated as potential treatments for iron overload disorders, where they can chelate excess iron and facilitate its removal from the body. Beyond their biomedical significance, Iron(III) complexes also find utility in catalysis, particularly in oxidation reactions. Iron(III) Schiff base complexes have been used as catalysts in the oxidation of organic substrates, such as alcohols and alkenes, under mild conditions. The redox-active nature of Iron(III) enables it to participate in various catalytic cycles, enhancing its versatility in synthetic chemistry.[18]

II. SYNTHESIS OF ZINC(II), MERCURY(II), AND IRON(III) COMPLEX

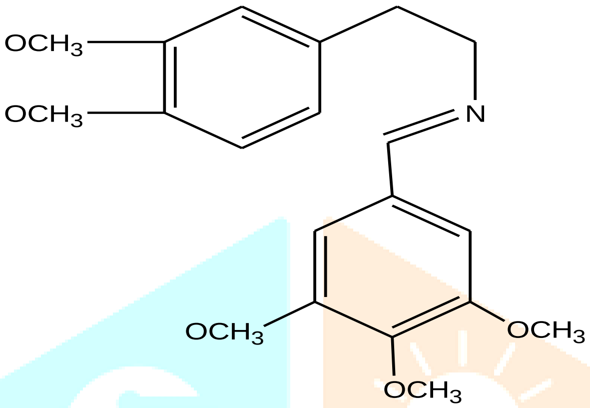
The synthesis of metal complexes involving Zinc(II), Mercury(II), and Iron(III) ions with organic multidentate chelating ligands represents a fascinating area of coordination chemistry with significant applications across biological, catalytic, and material sciences. These complexes are formed through the interaction between metal ions and organic ligands, which are typically derived from the condensation of a primary amine and an aldehyde or ketone. Zinc(II) complexes, for instance, are synthesized by reacting a zinc salt such as zinc acetate or zinc chloride with organic chelating ligands, such as bis(salicylaldehyde)ethylenediamine (Salen), in an appropriate solvent like ethanol or methanol.[19] The reaction occurs under controlled conditions, either at room temperature or under reflux, and results in products that exhibit antibacterial, anticancer, and antioxidant properties, as well as potential applications in gas storage and separation in metal-organic frameworks (MOFs). Similarly, Mercury(II) complexes are synthesized using mercury salts like mercury(II) chloride or mercury(II) acetate, with the reaction occurring in organic solvents such as chloroform or ethanol. These complexes, while studied for their antimicrobial and catalytic applications, are synthesized under inert conditions to prevent oxidation, and the resulting products are purified through filtration and drying under vacuum. Iron(III) complexes, on the other hand, are synthesized using iron salts such as ferric chloride, with organic ligands prepared from aldehydes and amines.[20] These reactions typically occur in solvents like methanol or ethanol and are conducted under either room temperature or reflux conditions. Iron(III) complexes are notable for their high reactivity, making them effective catalysts in oxidation-reduction reactions, as well as their applications in environmental remediation through Fenton-like reactions. Additionally, these complexes find use in biomedical applications, such as in magnetic resonance imaging (MRI), due to their paramagnetic properties. Overall, the synthesis of Zinc(II), Mercury(II), and Iron(III) complexes highlights their broad potential in various fields, from medicine and catalysis to environmental sustainability, thanks to the versatility of organic chelating ligands in forming stable and functionally diverse metal complexes.[21]

2.1. Synthesis of Zn (II) Complexes

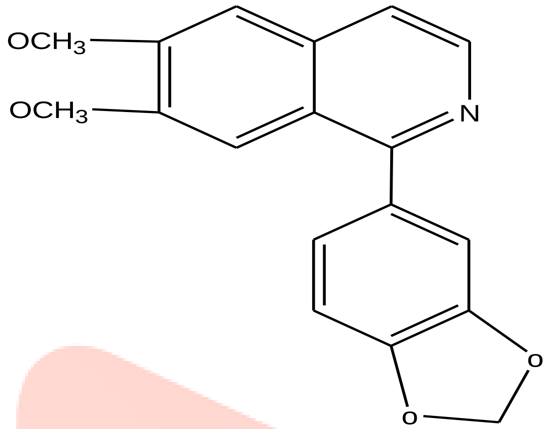
2.1.1 Synthesis of mononuclear complexes of ZN (II) with ligand 1 and 2

To synthesize the zinc complexes of ligands 1 and 2, a standard procedure was followed. First, ligand (1 mmol) and zinc acetate ($Zn(CH_3CO_2)_2$, 1 mmol) were dissolved separately in 25 mL of methanol. Once both solutions were prepared, they were combined, and the pH was adjusted to 7.5 ± 0.5 using a methanolic solution of potassium hydroxide (0.1%). The mixture was then refluxed for three hours to ensure complete reaction. After refluxing, the solvent was removed using a rotary evaporator. The obtained product was thoroughly washed with methanol before being dried.[22]

The synthesis yielded zinc(II) complexes, as illustrated in Figures 1 and 2. The product from the reaction, depicted in Scheme 3, was creamy yellow with a melting point between 56°C and 60°C. This complex demonstrated solubility in solvents such as ethanol, ether, methanol, 1% sodium hydroxide (NaOH), and 0.9% sodium chloride (NaCl), while it was insoluble in acetone, benzene, chloroform ($CHCl_3$), and hexane. Another product from a similar procedure was golden yellow, with an uncorrected melting point of 65°C



Ligand 1



Ligand 2

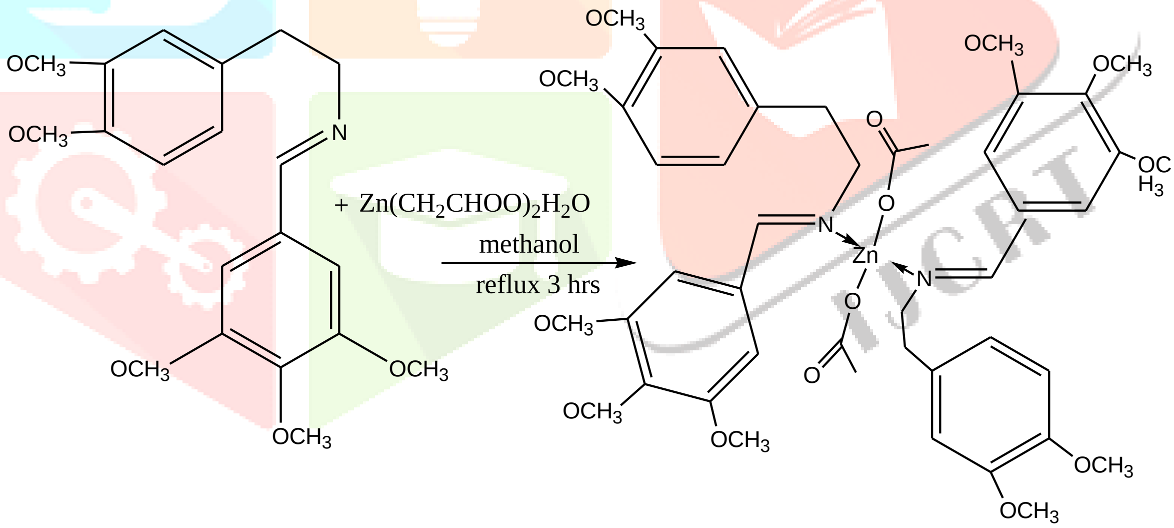


Figure 1: Synthesis of Zn(II) Complex of Ligand 1.

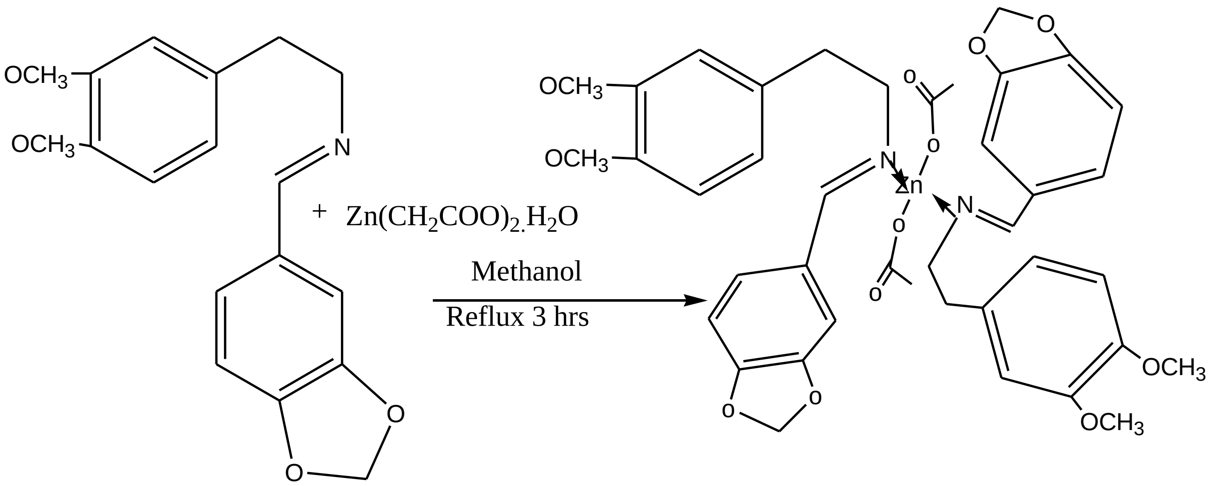


Figure 2: Synthesis of Zn(II) Complex of Ligand 2

The following general procedure was employed to synthesize zinc complexes of ligands 1 and 2. First, 1 mmol of the ligand and 1 mmol of zinc acetate dihydrate were each dissolved in 25 mL of methanol separately. Once the two solutions were mixed, a 0.1% potassium hydroxide solution in methanol was used to adjust the pH to approximately 7.5 ± 0.5. The mixture was then subjected to reflux for three hours. After refluxing, the solvent was removed using a rotary evaporator, and the resulting dried product was washed with methanol to purify it.

2.1.2 Synthesis of mononuclear complexes of ZN (II) with ligand 3 and 4

In a Schlenk tube equipped with a magnetic stir bar, 0.71 mmol of Schiff base pro-ligand 1 or 2, along with 2.1 mmol of potassium tert-butoxide and 3 mL of tetrahydrofuran (THF), were combined. After stirring the reaction mixture for 15 minutes, a dark red precipitate formed. Following this, a solution of 1.1 mmol of zinc nitrate hexahydrate, diluted in 1.5 mL of THF, was added along with 2.1 mmol of pyridine, and the mixture was stirred for an additional 15 minutes. The reaction continued with vigorous stirring at room temperature for 4 hours. Subsequently, the solvent was completely evaporated under reduced pressure. The resulting solid residue was then dissolved in dichloromethane, and the excess salts were removed by filtration. Finally, the solution was evaporated to dryness, yielding a solid sample of either complex 3 or 4, depending on the method employed.

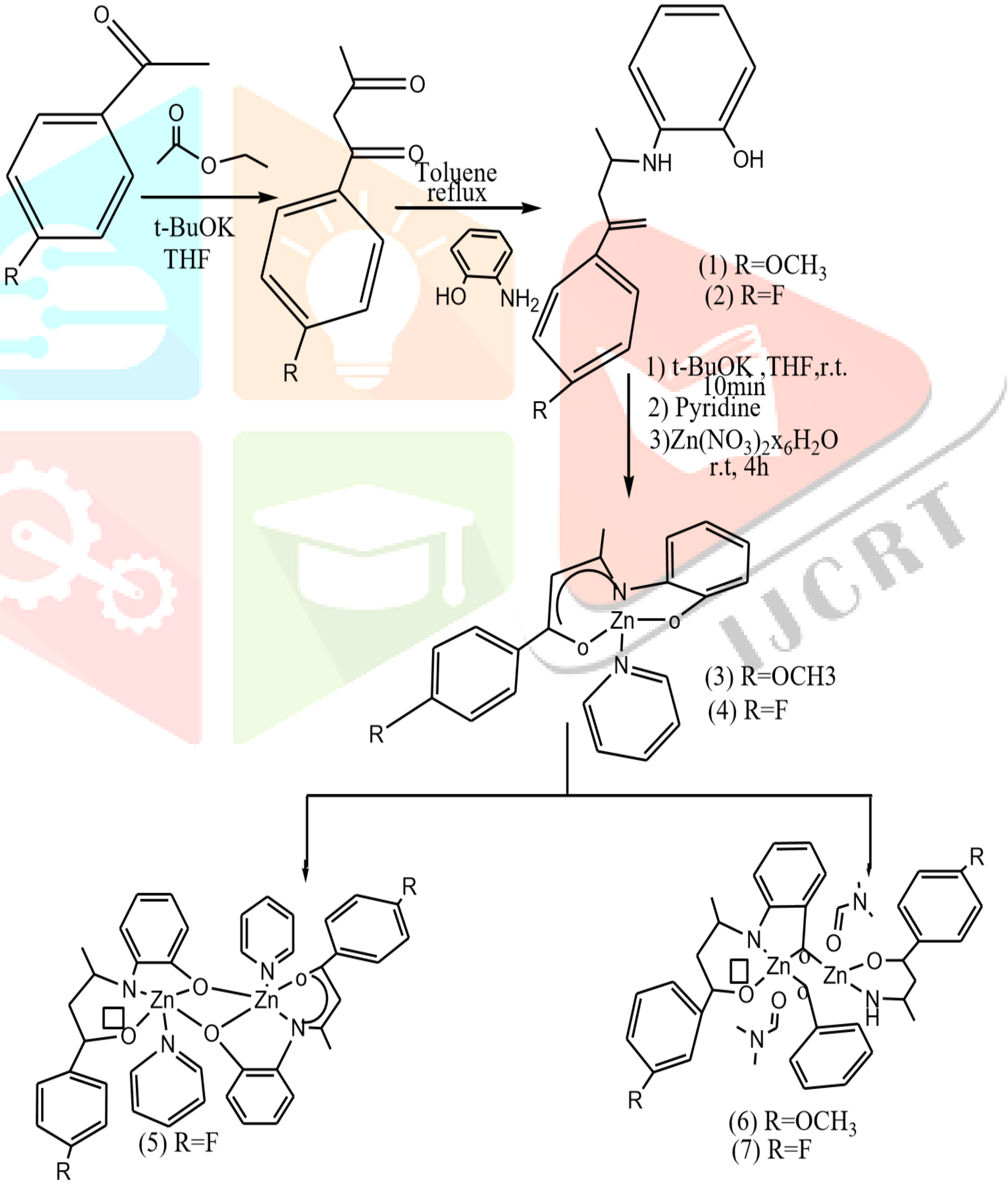


Figure 3: Synthesis of Zn (II) Complex.

2.2. Synthesis of Hg (II) Complexes

2.2.1 Synthesis of $[(\mu\text{-}Cl)_2\{Hg_2L_3Cl_2\}]_n$ complex

The complex $[(\mu\text{-}Cl)_2\{Hg_2L_3Cl_2\}]_n$ was prepared by heating mercury(II) chloride in the presence of a methanol solution of ligand L_1. The synthetic procedure for this complex is depicted in Figure 4.

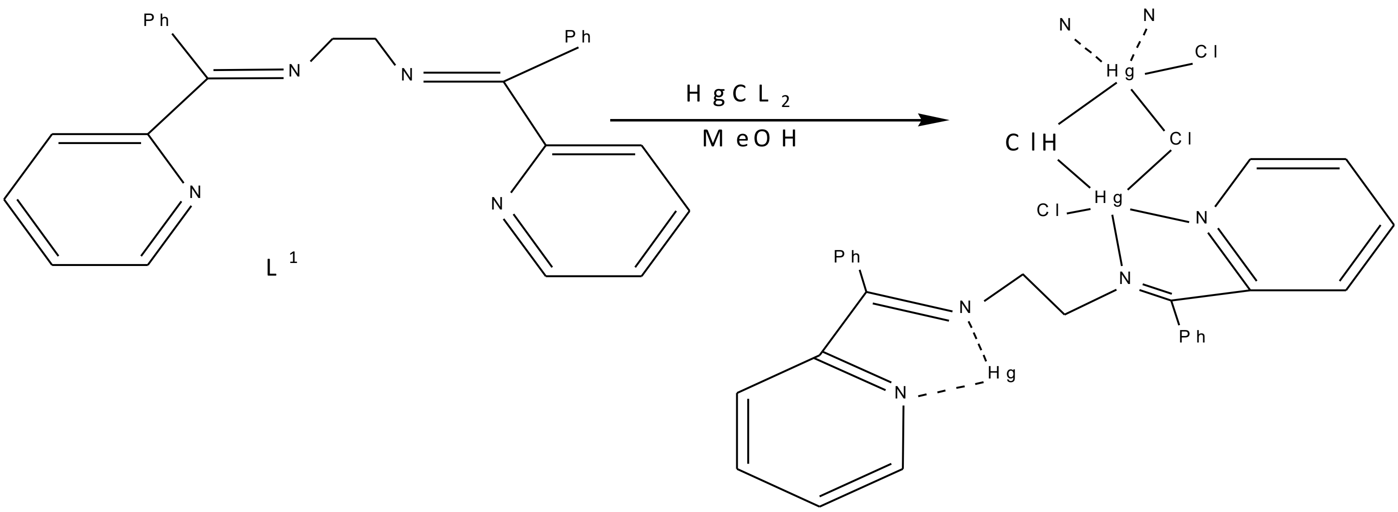


Figure: 4 Synthetic Route to Complex 2.2.1

2.2.2 Synthesis of [$Hg_2L_3Br_4$][(μ-Br)$_2${$Hg_2L_3Br_2$}]$_n$ complex

The complex [$Hg_2L_3Br_4$][(μ-Br)$_2${$Hg_2L_3Br_2$}]$_n$ was obtained by heating mercury(II) bromide with a solution of ligand L_1 in ethanol.[24] The synthetic method for this complex is shown in Figure 5.

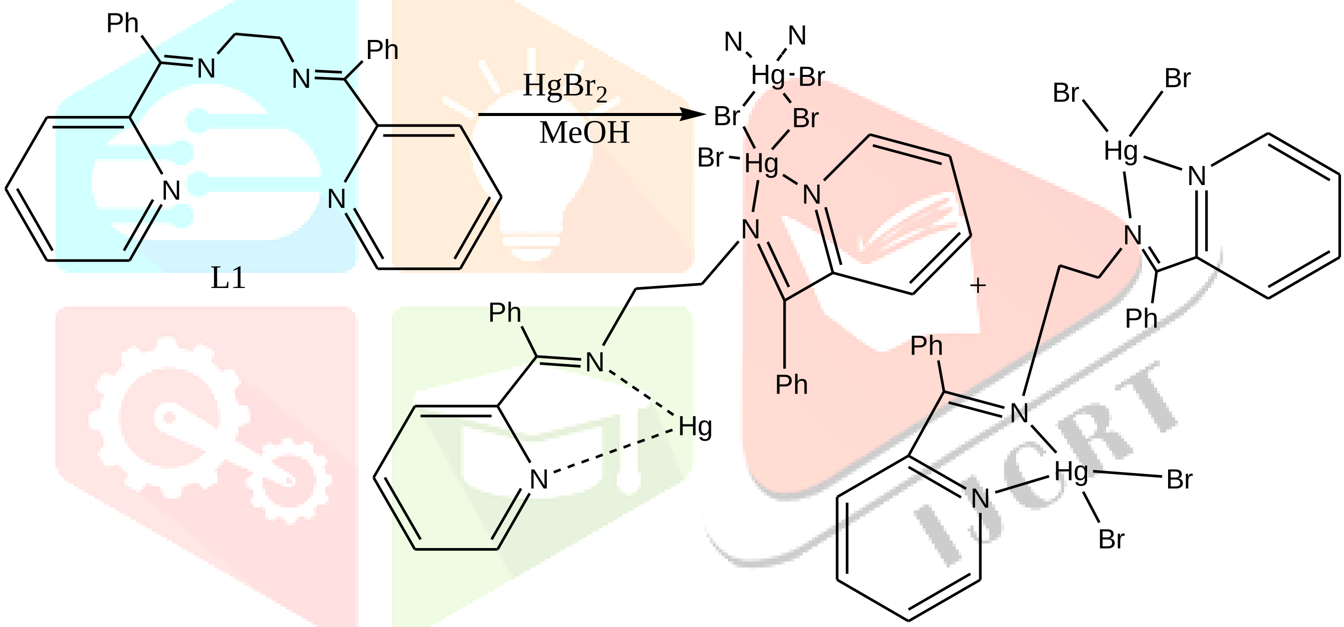


Figure: 5 Synthetic Route to Complex 2. 2.2

2.2.3 Synthesis of [(μ-Br)$_2${$Hg_2L_3Br_2$}]$_n$complex

A solution of ligand L_1 in acetonitrile was combined with a methanol solution of mercury(II) bromide to yield the complex [(μ-Br)$_2${$Hg_2L_3Br_2$}]. The synthetic procedure for this complex is illustrated in Figure 6.

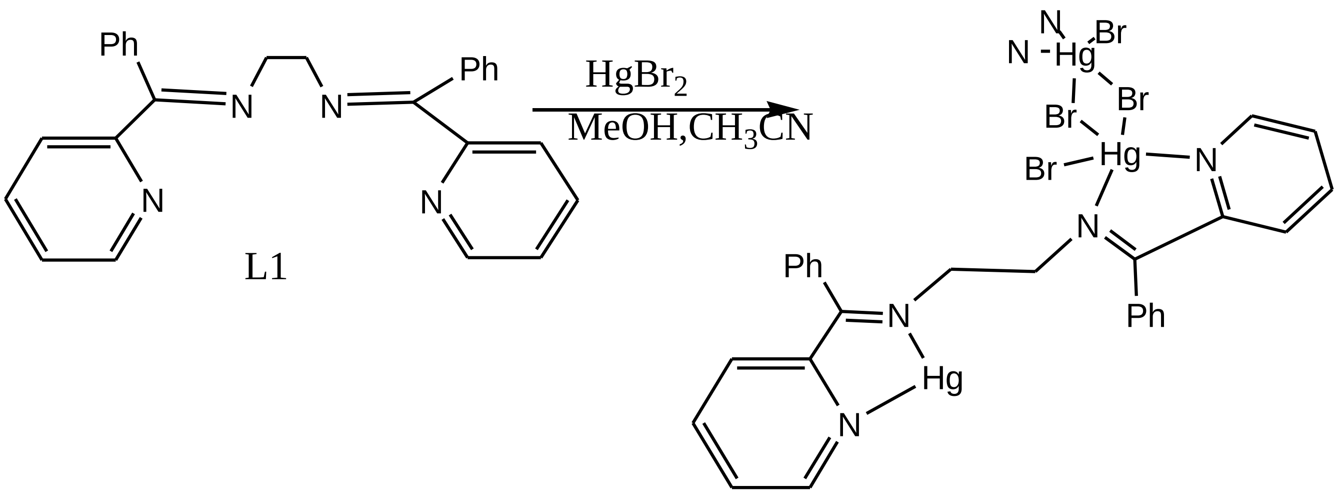


Figure: 6 Synthetic Route to Complex 2.2.3.

2.2.4 Synthesis of [$Hg_2L_3I_4$] complex

A methanol solution of mercury(II) bromide was mixed with a methanol solution of L_1 to produce the complex [$Hg_2L_3I_4$]. The synthetic pathway for this complex is shown in Figure 7.

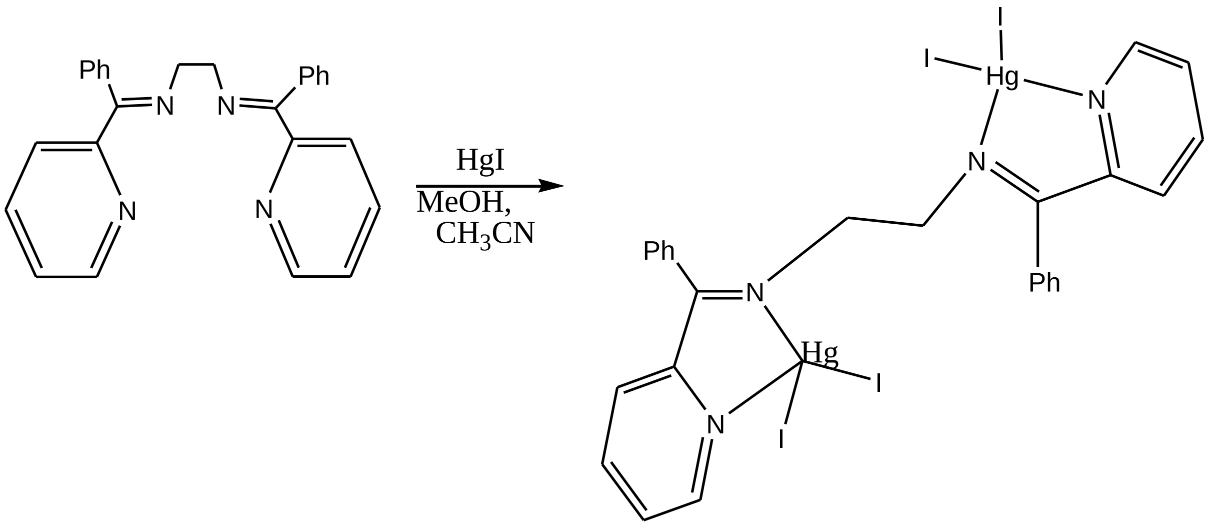


Figure: 7 Synthetic Route to Complex 2.2.4.

2.2.5 Synthesis of [$Hg_2L_1(SCN)_4$] complex

A methanol solution of mercury(II) acetate hydrate was added dropwise to a methanol solution of L_1 to yield the complex [$Hg_2L_1(SCN)_4$].[25] The synthetic pathway for this complex is illustrated in Fig. 8.

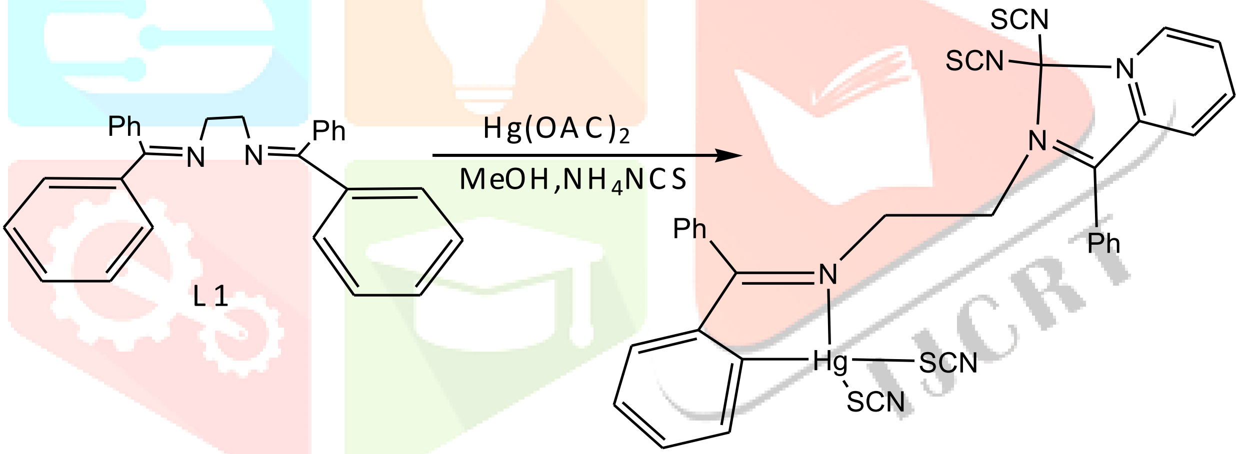


Figure: 8 Synthetic Route to Complex 2.2.5.

2.2.6 Synthesis of [$(-1,3\text{-}SCN)_2\{Hg_2L_1(SCN)_2\}]_n$ complex

The complex [$(-1,3\text{-}SCN)_2\{Hg_2L_1(SCN)_2\}]_n$ was obtained by heating a methanol solution containing mercury(II) thiocyanate and L_1. The synthesis procedure for complex is depicted in Figure 9.

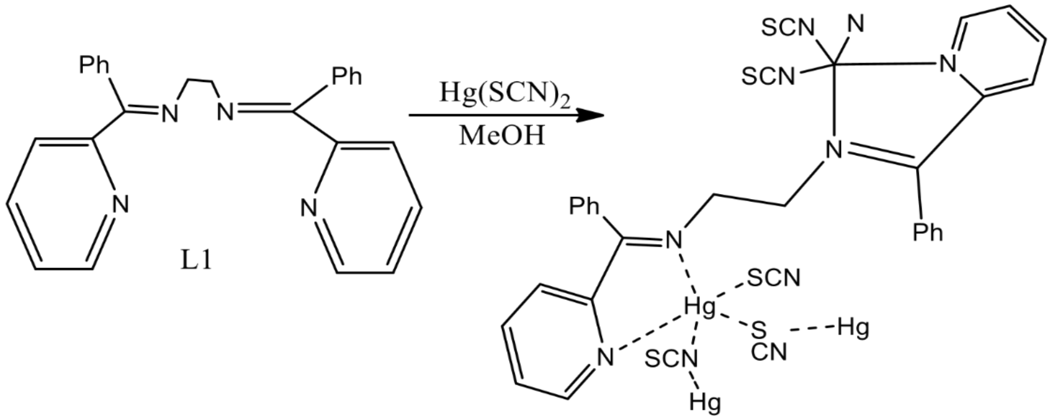


Figure: 9 Synthetic Route to Complex 2.2.6

2.2.7 Synthesis of $[HgL_2Cl]_2[Hg_2Cl_6]$ complex

The complex $[HgL_2Cl]_2[Hg_2Cl_6]$ was formed by heating a methanol solution of mercury(II) chloride with a methanol solution of L2. The synthesis pathway for complex is illustrated in Figure 10.

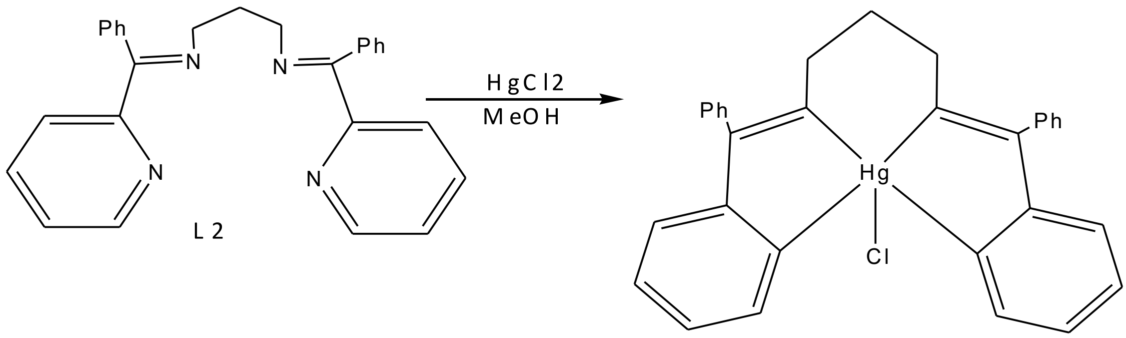


Figure: 10 Synthesis Route of Complex 2.2.7.

2.2.8 Synthesis of $[Hg(L_2)(\text{-}I)HgI_3]$ complex

A methanol solution of mercury(II) iodide was heated at 60°C with a methanol solution containing L2 to yield $[Hg(L_2)(\text{-}I)HgI_3]$.[26] The synthesis pathway for complex is illustrated in Figure 11.

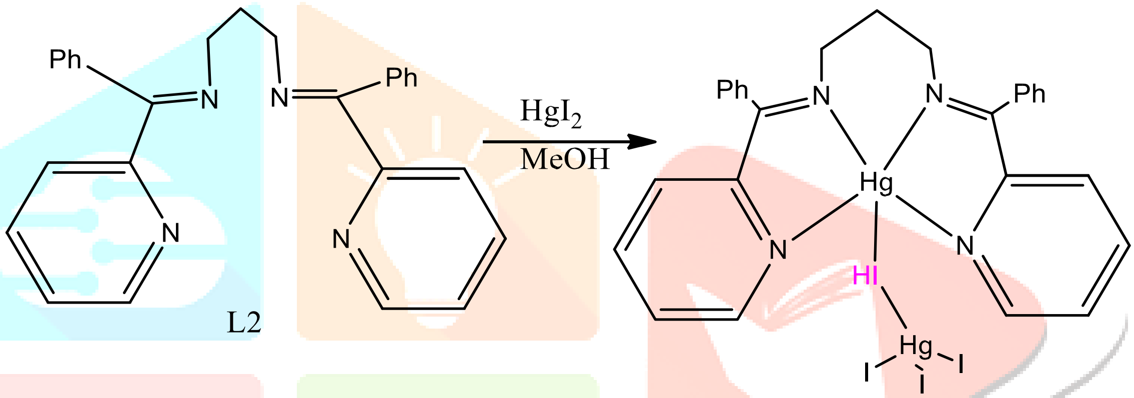


Figure: 11 Synthesis Route of Complex 2.2.8.

2.2.9 Synthesis of $[(\text{-}Cl)_2\{Hg_2L_3.Cl_2\}]n\ CH_2Cl_2$ complex

The complex $[(\text{-}Cl)_2\{Hg_2L_3.Cl_2\}]_n\ CH_2Cl_2$ was formed by mixing a methanol solution of mercury(II) chloride with a methanol solution of L_3.[27] The synthesis route for complex is illustrated in Figure 12.

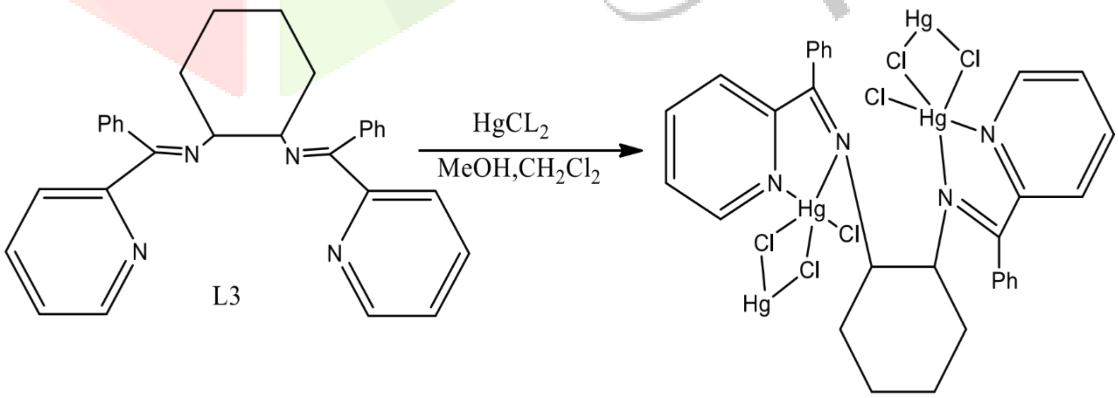


Figure: 12 Synthesis Route of Complex 2.2.9.

2.2.10 Synthesis of $[Hg_2L_4Cl_4]$ complex

L_4 was reacted with a mercury(II) chloride solution to produce $[Hg_2L_4Cl_4]$. The synthetic pathway for complex is depicted in Figure 13.

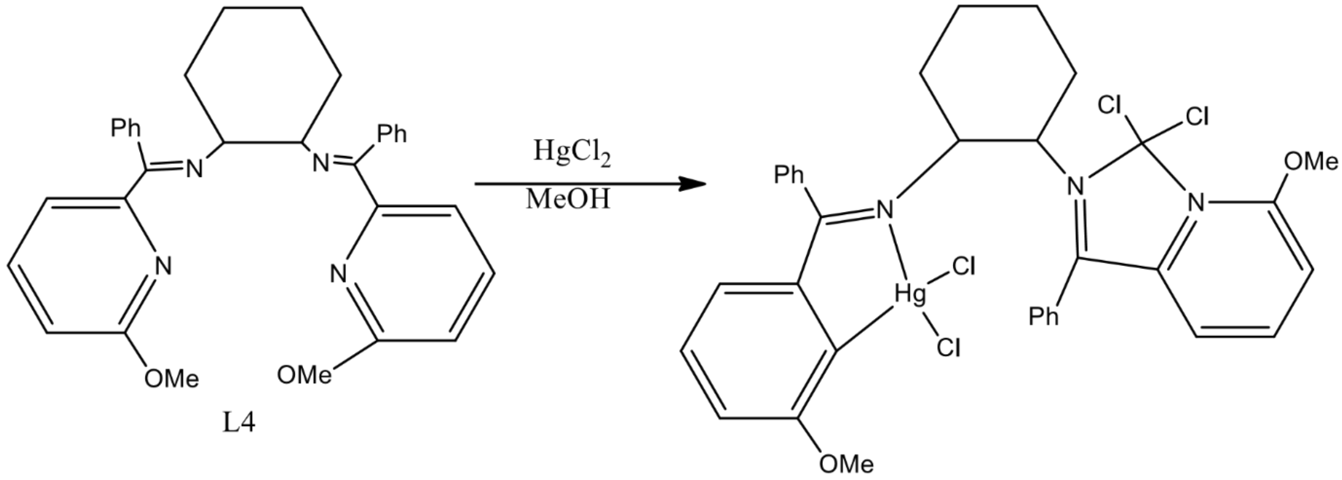


Figure: 13 Synthesis Route of Complex 2.2.10.

2.2.11 Synthesis of Hg(II) complex (HMBT-Hg)

The Hg(II) complex, referred to as HMBT-Hg, was synthesized by gradually adding a heated methanol solution containing 0.367 g (0.001 mol) of the HMBT ligand and 0.543 g of $HgCl_2$ (0.002 mol in 10 mL) to a mixture of methanol and DMF (90/10, 20 mL). A few drops of triethylamine were incorporated into the reaction mixture. The resulting solution was stirred and refluxed for two hours, during which a faint greenish-yellow precipitate became evident. To ensure complete precipitation of the product, the reaction continued for an additional hour. The precipitate was filtered to separate it from the solvent, followed by several rinses with hot methanol and ether. The final product was then placed under vacuum to dry over anhydrous $CaCl_2$. The yield was 58.5%, and the complex exhibited a greenish-yellow color. Conductivity measurements showed a value of 18.3 ohm^{-1} cm^2 mol^{-1} at 10^{-3} M in DMSO. ESI-MS analysis indicated a molecular weight of m/z = 933.29 g/mol [MH_2O] and a calculated value of 933.86 [28].

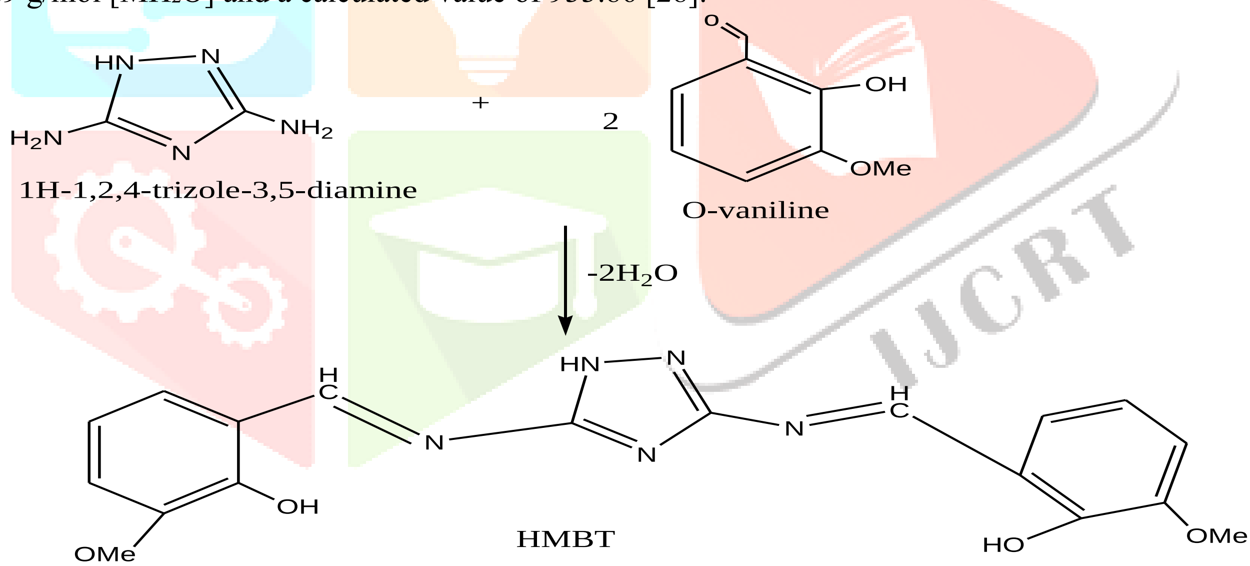


Figure: 14 Synthetic Route to Complex 2.2.11.

2.2.12 Synthesis of [$HgCl_2L$]$_2$ Complex

The synthesis of 1-(1H-benzo[d]imidazol-2-yl)ethan-1-one was accomplished in two main steps. Initially, o-phenylenediamine was reacted with lactic acid to form 1-(1H-benzo[d]imidazol-2-yl)ethanol. This compound was then oxidized to produce 2-acetylbenzimidazole. The resulting intermediate was subsequently reacted with p-anisidine to generate a Schiff base. This Schiff base was directly reacted with mercury chloride in acetonitrile at room temperature, yielding the mercury complex [$HgCl_2L$]$_2$. Conducting the reaction as a one-pot process, without isolating the Schiff base, resulted in a high yield of 92% for the final complex. The mercury complex exhibited air stability, had a high melting point, and its molecular structure was characterized through IR and UV-vis spectroscopy, as well as single crystal X-ray diffraction. [29]

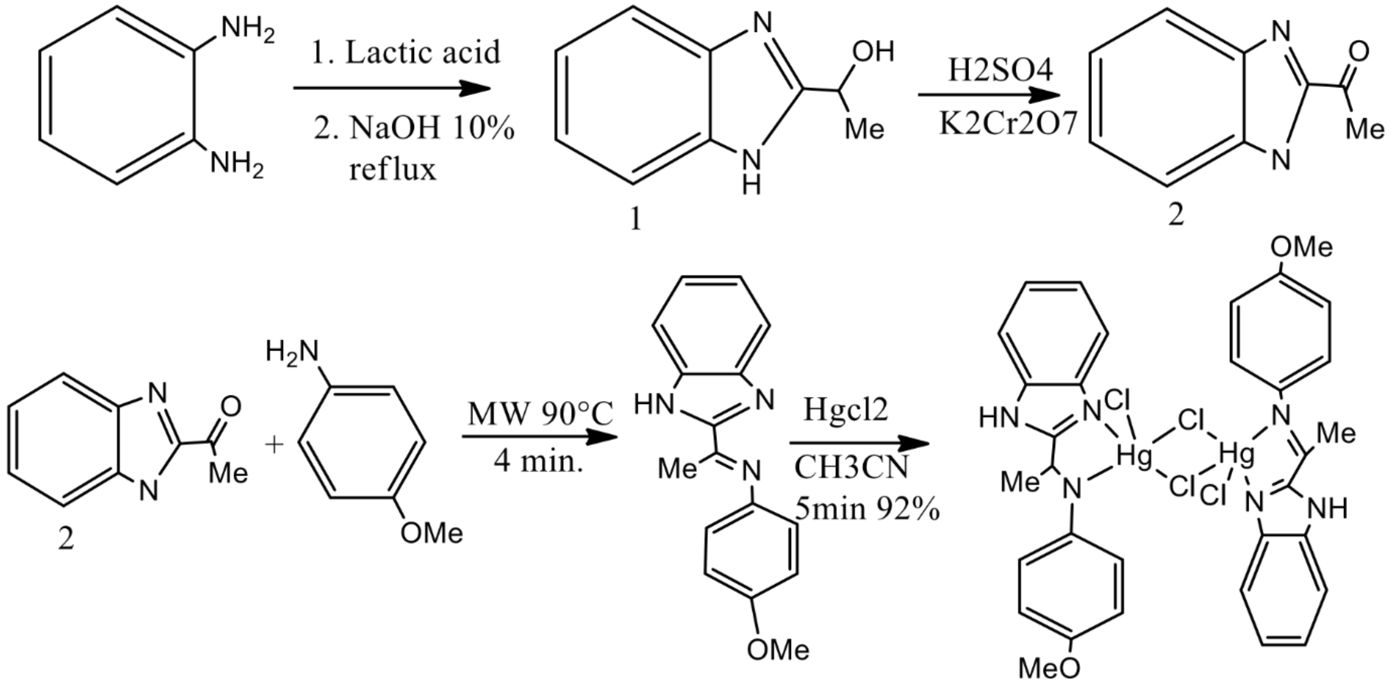


Figure: 15 Synthetic Route to Complex 2.2.12

2.2.13 Synthesis of [Hg((2,6-Cl-ba)2 en)Br$_2$] Complex

The synthesis of mercury(II) complexes using unique ligands known as symmetric bidentate Schiff bases. In this report, we detail the synthesis of these complexes, examine their structures through various spectroscopic techniques, and analyze their crystalline forms, particularly concentrating on the Schiff base ligand (2,6-Cl-ba)$_2$en, as illustrated in Figure 16.[30]

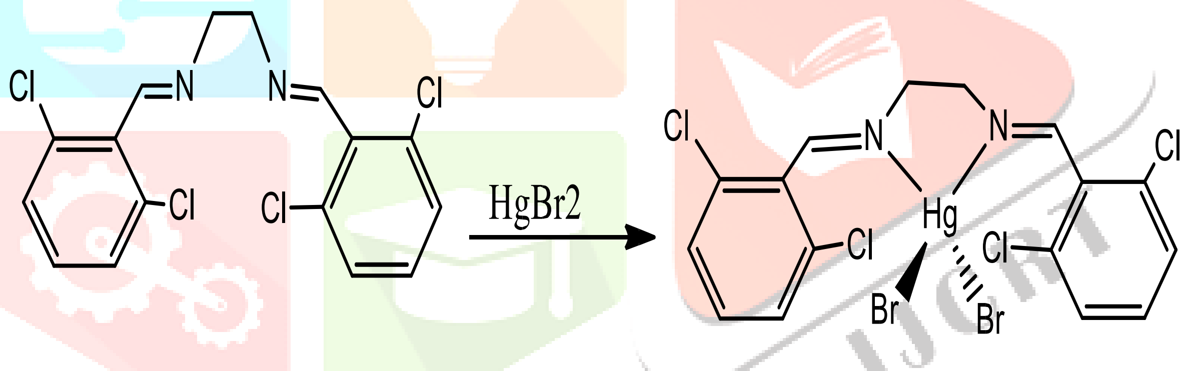


Figure: 16 Synthetic Route to Complex 2.2.13

2.2.14 Synthesis of Hg(II) complex

The mercury complex was prepared by combining a solution of the metal salt (0.0015 mol in 10 mL of ethanol) with a ligand solution (0.0015 mol, 0.6865 g), as shown in Fig. 17. The mixture was refluxed for about 7 hours. After refluxing, the resulting product was collected by filtering through filter paper and washed with ethanol and diethyl ether. The purified HgLCl$_2$ complex (where L = $C_{20}H_{34}N_4S_4$) was then dispersed in distilled water.

Next, 1 gram of polyvinyl alcohol (PVA) was dissolved in 40 mL of distilled water to create a 2.5% PVA solution, which was stirred for approximately 1 hour at 80 °C. After allowing the PVA solution to cool to room temperature over about 2 hours, the prepared HgLCl$_2$ metal complex was added to the PVA solution while stirring continuously, forming the PVA composite via the solution casting method. The pure PVA and the PVA doped with the Hg(II) metal complex were designated as SPNC-0 and SPNC-1, respectively.[31]

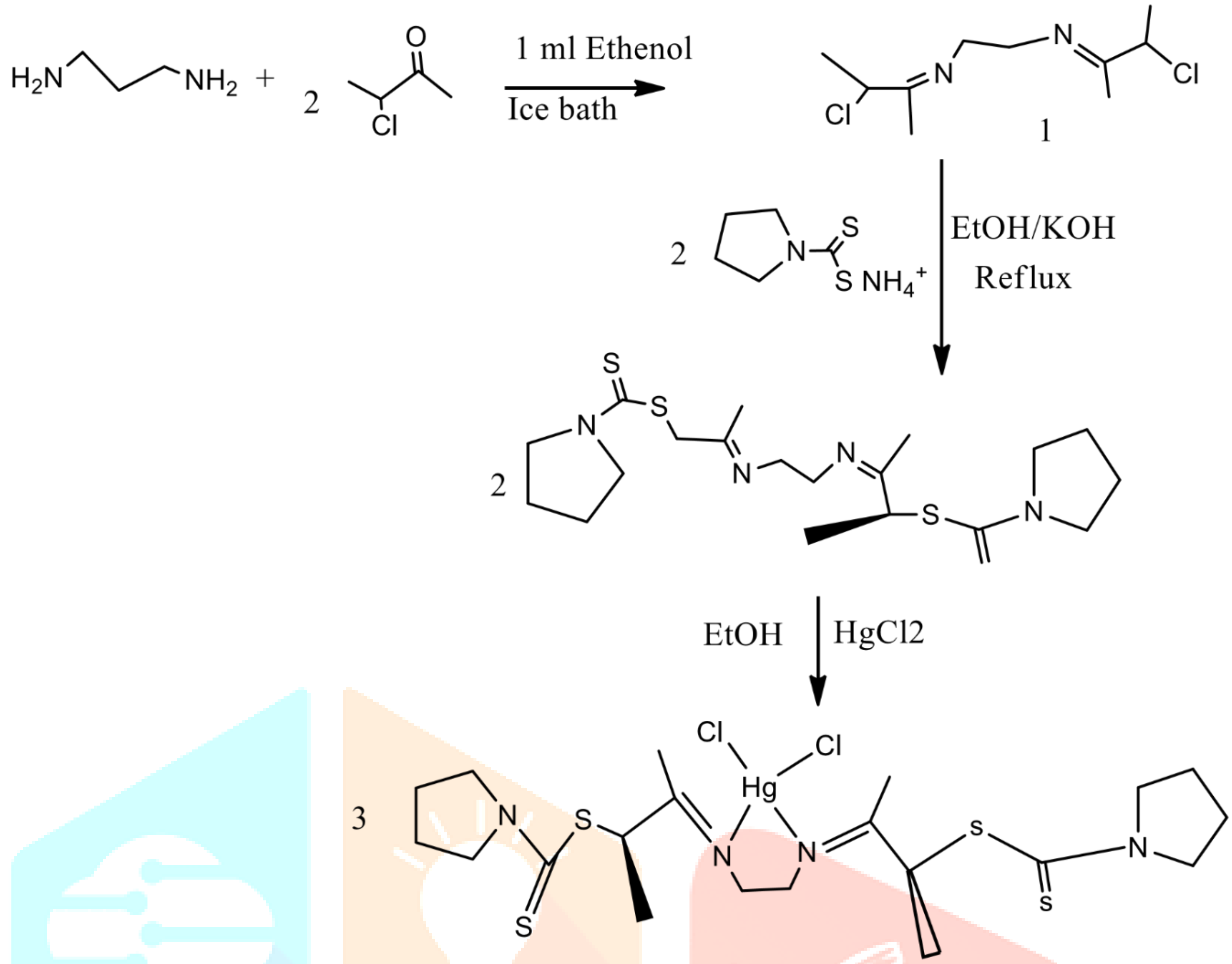


Figure: 17 Synthetic Route to Complex 2.2.14.

2.2.15 Synthesis of Hg(II) complex

A solution of hydrated $HgCl_2$ (1.0 mmol) was prepared by dissolving it in hot ethanol (25 mL) and then mixed with an ethanolic solution (25 mL) of H_2IPH (1.0 mmol). The reaction mixture was refluxed for 4 hours. The resulting fine solid complexes were collected by filtration, washed with a small amount of ethanol and ether, and then dried in a desiccator over anhydrous $CaCl_2$. The complexes exhibited stability in air.[32]

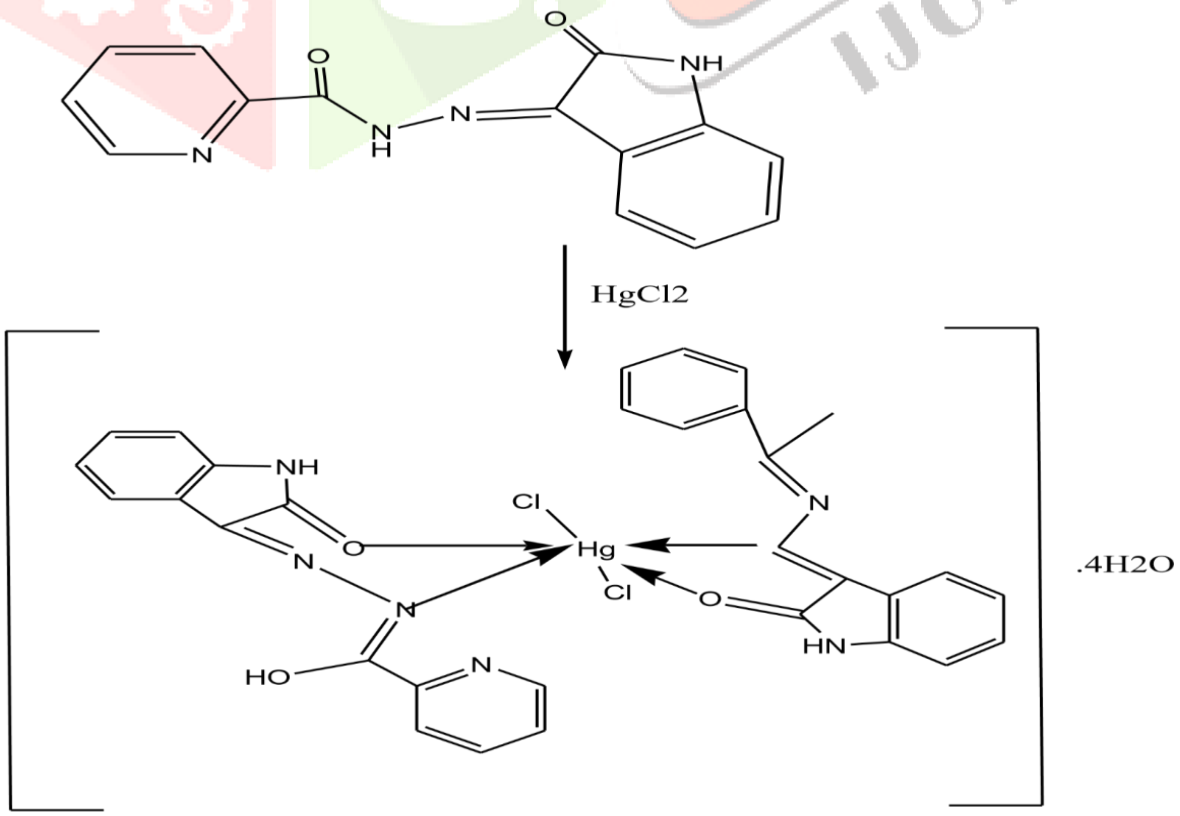


Figure: 18 Synthetic Route to Complex 2.2.15.

2.3. Synthesis of Fe(III) Complexes

Iron complexes of ligands 1 and 2 were synthesized using the following general procedure. A solution of the ligand (1 mmol) was prepared in 25 mL of ethanol, followed by a solution of ferric trichloride (1 mmol) in the same volume of ethanol. The two solutions were combined in a 250 mL round-bottom flask equipped with magnetic stirring.[33] The mixture was refluxed for 50 minutes while stirring continuously. After refluxing, the mixture was allowed to cool to room temperature, and the resulting solids were filtered out. The solids were then recrystallized using methanol, and the process was completed under vacuum.

The product, shown in Figures 20 and 21, had a melting point of 97°C and was light brown in color. It was completely insoluble in chloroform and ether but showed slight solubility in acetone, benzene, ethanol, hexane, and 1% NaOH and 0.9% NaCl. Additionally, it was highly soluble in DMSO. Another iron complex produced had a chocolate brown color and an uncorrected melting point of 160°C.[34] This complex was insoluble in benzene but readily dissolved in DMSO and methanol, with limited solubility in acetone, chloroform, ethanol, ether, and hexane, as well as in 1% NaOH and 0.9% NaCl.[35]

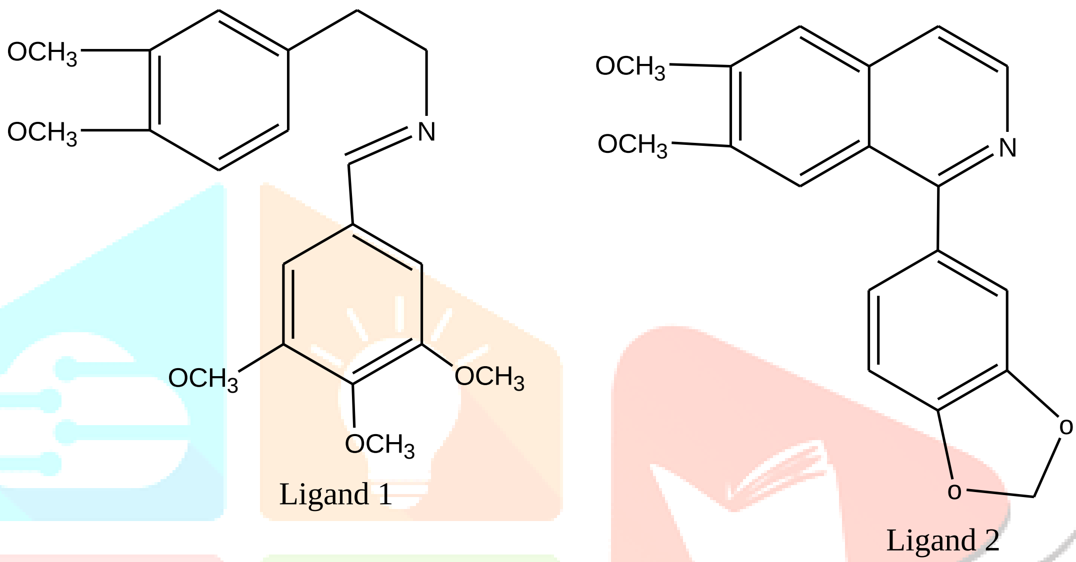


Figure: 19

Iron(III) monodentate Schiff base metal complexes have attracted considerable interest in coordination chemistry because of their unique structural features and diverse applications. These complexes are created by coordinating iron(III) ions with Schiff base ligands, which are produced through the condensation of primary amines with aldehydes or ketones. This reaction results in Schiff base ligands that contain an imine group (C=N), which plays a key role in establishing stable and effective metal-ligand interactions with iron(III) ions.[36]

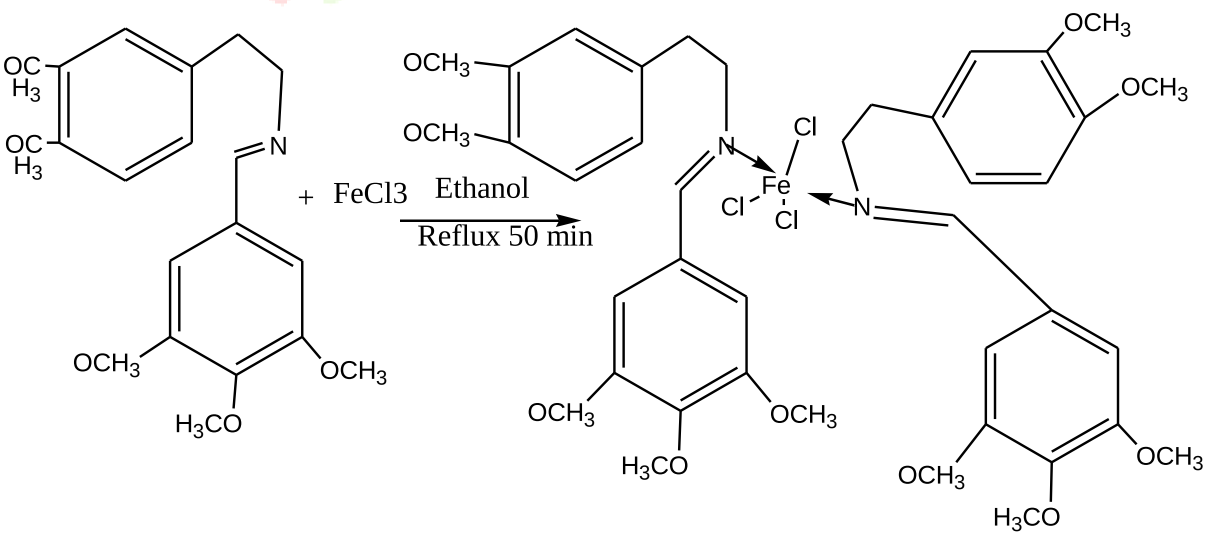


Figure: 20 Iron(III) Complex of Ligand 1.

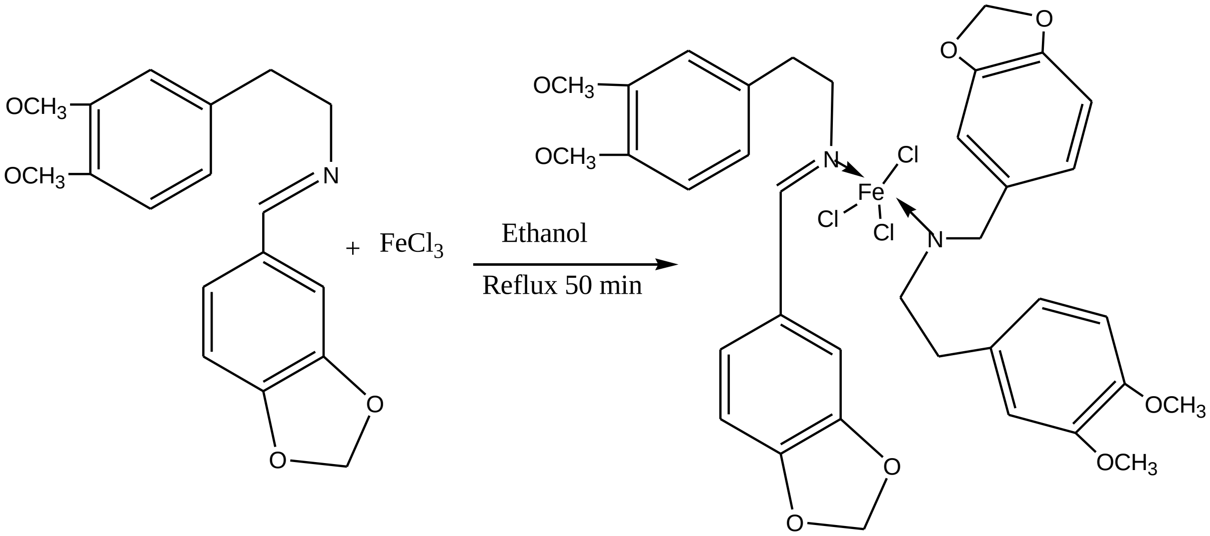


Figure: 21 Iron(III) Complex of Ligand

The synthesis of Iron(III) monodentate Schiff base complexes generally involves the reaction of iron salts, such as ferric chloride ($FeCl_3$) or ferric nitrate ($Fe(NO_3)_3$), with Schiff base ligands. The adaptability of Schiff base ligands stems from their ability to be synthesized from a wide range of primary amines and aldehydes or ketones, allowing for the creation of various ligands. This versatility enables researchers to design ligands with specific electronic and steric properties, tailored to produce metal complexes with distinct characteristics suitable for different applications.[37]

Several factors influence the synthesis process, including the choice of solvent, temperature, pH, and reaction time. Modifying these parameters can affect the yield and properties of the Iron(III) monodentate Schiff base complexes, allowing for optimization to meet specific needs. This flexibility enhances the value of these complexes in both scientific research and practical applications, as their properties can be finely adjusted to align with various demands.[38]

To thoroughly understand and utilize Iron(III) monodentate Schiff base complexes, several key characterization techniques are employed. UV-Vis spectroscopy examines electronic transitions within the complexes, providing insights into the ligand field environment and metal-ligand interactions. Infrared (IR) spectroscopy identifies the functional groups in the ligands and confirms the coordination of the Schiff base to the iron center through specific vibrational modes. Nuclear Magnetic Resonance (NMR) spectroscopy offers detailed information about the electronic environment surrounding the nuclei in both the ligand and the metal center, revealing the structure and dynamics of the complexes. Lastly, X-ray crystallography determines the three-dimensional structure of the complexes, clarifying the precise arrangement of atoms and the geometry around the iron center.[39]

III. CHARACTERIZATION TECHNIQUES

3.1. Spectroscopic Techniques

3.1.1. UV-Visible Spectroscopy

UV-Visible spectroscopy is a widely used analytical technique for characterizing metal complexes, particularly those involving transition metals. This method relies on the interaction between ultraviolet or visible light and the electronic structure of compounds, offering insights into electronic transitions and structural properties. When a sample is irradiated with UV or visible light, electrons in the ground state can be excited to higher energy levels. The energy difference between these levels corresponds to the wavelength of absorbed light. In transition metal complexes, this absorption is primarily due to d-d electronic transitions, where electrons are promoted between d-orbitals. The d-orbitals of transition metals are split into different energy levels due to the ligand field created by surrounding ligands, and this splitting gives rise to distinct electronic transitions. In addition to d-d transitions, metal complexes may also exhibit charge transfer transitions, such as metal-to-ligand or ligand-to-metal charge transfer, which contribute to the absorption spectrum at higher energy levels.[40]

The quantitative analysis of UV-Visible spectroscopy follows the Beer-Lambert Law, which relates absorbance to the concentration of the absorbing species, the path length, and the molar absorptivity. This allows for the determination of the concentration of metal complexes in solution by measuring their absorbance at specific wavelengths. The technique provides valuable information about the electronic properties and coordination environment of metal complexes. For instance, it helps identify the presence of specific metal ions based on their characteristic d-d transition energies and determines the ligand field strength and coordination geometry around the metal center. The splitting of d-orbitals and the position of absorption maxima are influenced by the nature of the ligands and their spatial arrangement, allowing researchers to infer details about ligand strength and coordination geometry, such as whether the complex has an octahedral, tetrahedral, or square planar structure.

UV-Visible spectroscopy is applied across various fields, including chemistry, biochemistry, materials science, and environmental science. It is commonly used to characterize newly synthesized metal complexes, providing confirmation of successful ligand coordination and insights into the geometry of the complex. The technique also plays a crucial role in comparing ligand field strengths among different metal complexes, which is important for understanding the efficiency of metal complexes in catalysis and materials science. Additionally, UV-Visible spectroscopy helps assess the stability and purity of metal complexes, enabling researchers to monitor changes in absorbance over time to evaluate stability under different conditions or to detect impurities. In biochemistry, the technique is used to study metalloproteins and metalloenzymes, where it reveals the coordination environment of metal ions involved in enzyme activity. It is also employed in environmental chemistry to detect and quantify metal pollutants in water samples, as well as in studying reaction kinetics involving metal complexes by monitoring changes in absorbance during chemical reactions. Despite its advantages, UV-Visible spectroscopy has limitations. Overlapping absorption peaks in complex mixtures can complicate the interpretation of spectra, making it difficult to assign specific peaks to individual complexes. The technique also does not provide detailed structural information, often requiring complementary methods like NMR spectroscopy or X-ray crystallography for a complete molecular understanding. Solvent effects can influence absorption spectra, causing shifts in wavelengths that must be accounted for during interpretation. Furthermore, the Beer-Lambert Law only applies within a certain concentration range, and at high concentrations, deviations from linearity may lead to inaccurate concentration determinations. Therefore, ensuring that concentrations fall within the applicable range is crucial for obtaining reliable results.[41]

3.1.2. Infrared (IR) Spectroscopy

Spectroscopic techniques, such as Infrared (IR) spectroscopy and Nuclear Magnetic Resonance (NMR) spectroscopy, are crucial for characterizing metal complexes, providing insights into their molecular structure, bonding, and dynamics. These methods offer complementary information about ligand coordination and the electronic environments of metal complexes.

Infrared (IR) spectroscopy operates on the principle that molecules absorb infrared radiation at specific wavelengths corresponding to the vibrational transitions of their bonds. When exposed to IR radiation, the energy absorbed promotes vibrational motion within the molecule. In metal complexes, the coordination of ligands to metal ions alters the vibrational frequencies of ligand bonds due to metal-ligand interactions. This makes IR spectroscopy highly effective for studying structure and bonding. The technique provides essential information such as the identification of functional groups, as each exhibits characteristic absorption bands in the IR spectrum. This allows researchers to confirm the chemical structure of ligands in metal complexes. Additionally, the coordination mode of ligands, whether monodentate, bidentate, or tridentate, can be inferred from shifts in the vibrational frequencies of bonds involved in coordination (such as C–O, C–N, and M–O). Changes in these frequencies often indicate the formation of complexes, with shifts in absorption bands signaling changes in bond strength and the surrounding molecular environment.[42]

IR spectroscopy is used extensively to confirm the coordination of ligands to metal ions. By comparing the IR spectra of free ligands and their metal complexes, researchers can determine the success of coordination, as indicated by the appearance of new bands or shifts in existing ones. Moreover, the technique helps investigate ligand dynamics, as changes in vibrational frequencies can reveal ligand flexibility, conformational shifts, or solvent interactions. IR spectroscopy is also applied in biochemistry, particularly in the study of metalloproteins and metalloenzymes, where it identifies specific functional groups and their interactions with metal ions, thus contributing to a deeper understanding of biological mechanisms.[43]

3.1.3. Nuclear Magnetic Resonance (NMR) Spectroscopy

Nuclear Magnetic Resonance (NMR) spectroscopy is a powerful tool that utilizes the magnetic properties of certain atomic nuclei, such as hydrogen (^1H) and carbon (^13C), to gain detailed insights into the electronic environments of atoms in a molecule. In the presence of a strong magnetic field, these nuclei absorb and re-emit electromagnetic radiation at specific frequencies, which correspond to their electronic environment. In metal complexes, NMR spectroscopy is invaluable for understanding the coordination environment and dynamics of both the metal center and its ligands.[44]

One of the key features of NMR spectroscopy is the chemical shift, which reflects the electronic environment surrounding nuclei like protons or carbons. In metal complexes, the chemical shifts of ligands can indicate how their electron density is affected by coordination with the metal. Shifts in these values upon complex formation provide insight into the nature of the metal-ligand interactions. Additionally, NMR spectroscopy provides information about the coordination environment of the metal center, such as the number and types of ligands attached. By analyzing the NMR signals from ligand atoms, researchers can infer the geometry of the coordination sphere and the number of coordinating atoms.

NMR spectroscopy also excels in studying the dynamics of metal complexes, offering information on processes like ligand exchange and conformational changes. Relaxation times and line shapes observed in NMR spectra can reveal the rates of ligand exchange, rotational dynamics, and overall molecular mobility. This makes NMR particularly useful for examining the behavior of metal centers and ligands in solution.

Applications of NMR spectroscopy in metal complex characterization are broad. The technique plays a critical role in structural determination, often in combination with computational methods, allowing researchers to construct detailed models based on chemical shifts and coupling patterns. It also enables the investigation of ligand coordination by tracking changes in chemical shifts, providing insights into the strength and nature of metal-ligand interactions. Furthermore, NMR spectroscopy is a powerful tool for studying the kinetics of ligand exchange processes, helping researchers monitor these changes over time to extract kinetic parameters that shed light on coordination and reactivity dynamics.[45]

In biochemical research, NMR spectroscopy is widely used to study metalloproteins. It reveals essential details about metal binding sites, ligand orientations, and protein-ligand interactions, contributing significantly to the understanding of enzyme mechanisms and various biological processes.

3.2. Crystallography

Single-Crystal X-ray Diffraction (SCXRD) is a highly effective analytical technique used in crystallography to determine the molecular structures of various compounds, including metal complexes. This method is essential for chemists, materials scientists, and biochemists, as it provides detailed insights into the atomic arrangement within a crystal lattice. By analyzing the diffraction patterns that result when X-rays interact with a crystalline sample, researchers can uncover valuable information about molecular geometries, bonding environments, and the spatial arrangement of ligands around metal centers.

The principle behind SCXRD involves the interaction of X-rays with a crystalline material. When X-rays are directed at a single crystal, the atoms within the crystal lattice cause the X-rays to scatter in specific directions, creating a diffraction pattern characterized by constructive and destructive interference. This pattern is recorded by a detector and contains information about the crystal lattice planes' spacing and orientation, which allows the determination of atomic positions within the crystal. SCXRD analysis involves several steps, starting with data collection, where the crystal is rotated in the X-ray beam to capture diffraction images from various angles. This comprehensive dataset is then used to solve the phase problem, a critical step in X-ray crystallography, as the recorded intensities do not directly provide the necessary phase information. Techniques like multiple wavelength anomalous dispersion (MAD) or direct methods are used to address this challenge. Once the data is collected, mathematical algorithms are employed to calculate the electron density map, representing the distribution of electrons within the molecule and enabling the placement of atoms within the lattice. This model is further refined iteratively to match the observed and calculated diffraction data, yielding a highly precise molecular structure.[46]

SCXRD offers critical information about metal complexes, including the accurate determination of molecular structure. This precision allows for the measurement of bond lengths and angles, essential for understanding the geometry and spatial orientation of metal-ligand interactions, which influence a complex's reactivity and stability. The technique also helps identify the coordination geometry of metal centers, such as octahedral, tetrahedral, or square planar geometries, which are key to understanding the electronic and steric properties of the metal complex. Additionally, SCXRD provides insights into the arrangement and orientation of ligands around the metal center, which is important for understanding how ligands affect the complex's properties, including its electronic behavior and potential applications in fields like catalysis or medicine.

SCXRD is considered the "gold standard" for determining the three-dimensional structures of metal complexes due to its accuracy and high resolution. Its applications are extensive, ranging from the structural elucidation of newly synthesized metal complexes to validating proposed structures and revealing their chemical behavior. SCXRD is also valuable for understanding reaction mechanisms by determining the structures of intermediates and products in catalytic reactions, helping design more efficient catalysts. The technique enables the study of specific interactions between metal ions and ligands, revealing how coordination changes affect the electronic properties of the metal complex. In drug design and development, SCXRD plays a crucial role in metallodrug design, allowing researchers to optimize interactions between metal-containing therapeutic agents and biological targets. In materials science, SCXRD is used to characterize coordination polymers and metal-organic frameworks (MOFs), providing insights into their structural properties and potential applications in gas storage, separation, and catalysis.[47]

3.3. Magnetic Susceptibility

Magnetic susceptibility is a crucial parameter for understanding the magnetic properties of materials, including metal complexes, by measuring how they respond to an external magnetic field. This technique provides insights into whether a material exhibits diamagnetic or paramagnetic behavior, helping to elucidate the electronic structure, oxidation states, and coordination geometries of metal complexes. When a sample is placed in a magnetic field, it experiences a force that can either enhance or oppose the field, and this response is quantified as its magnetic susceptibility (χ). The principle behind magnetic susceptibility is based on the interaction between the material and the magnetic field, with two main types of magnetic behavior observed: diamagnetism and paramagnetism. Diamagnetic materials, which have no unpaired electrons, develop an induced magnetic moment in the opposite direction of the applied field, resulting in negative magnetic susceptibility. This effect is typically weak and occurs in all materials, but is overshadowed in those with paramagnetic or ferromagnetic behavior. In contrast, paramagnetic materials, which have unpaired electrons, align with the magnetic field, leading to positive magnetic susceptibility. The strength of this response depends on the number of unpaired electrons and their spin states.[48]

To measure magnetic susceptibility, various techniques such as the Gouy balance, Faraday balance, and SQUID (Superconducting Quantum Interference Device) magnetometry are employed. These methods allow the quantification of a sample's magnetic response, providing valuable information about its magnetic characteristics. Magnetic susceptibility measurements offer critical insights into the electronic and structural properties of metal complexes. They reveal the oxidation state and electronic configuration of the metal ion, as susceptibility is directly related to the number of unpaired electrons, which correlates with the metal's oxidation state. Higher oxidation states generally have fewer unpaired electrons and thus lower susceptibility, while lower oxidation states correspond to more unpaired electrons and greater paramagnetic behavior. Magnetic susceptibility also provides information on the coordination geometry of the metal complex. Different geometries, such as octahedral or tetrahedral, influence the arrangement of d-orbitals and, subsequently, the number of unpaired electrons. For example, in octahedral complexes, crystal field splitting alters the electron distribution among d-orbitals, affecting susceptibility. Additionally, susceptibility data can be used to determine the number of unpaired electrons through the calculation of the effective magnetic moment, which is related to the electron count and helps quantify the metal center's electronic configuration.

The applications of magnetic susceptibility measurements in studying metal complexes are extensive. In transition metal complex characterization, magnetic susceptibility helps differentiate between oxidation states, ligands, and coordination geometries, providing insight into electronic structure and reactivity. In catalysis, paramagnetic metal complexes often exhibit unique properties due to their unpaired electrons, which influence reaction mechanisms. Understanding these magnetic properties aids in the design of more efficient catalysts. Magnetic susceptibility also plays a role in the study of metalloenzymes and metalloproteins, where the metal center is critical to biological functions. By assessing magnetic behavior, researchers can gain insights into the electronic structures and mechanisms of these biological complexes, contributing to biochemistry and medicine. In materials science, magnetic susceptibility is used to investigate the magnetic properties of coordination polymers and metal-organic frameworks (MOFs), which often exhibit tunable magnetic behavior based on the choice of metal ions and ligands. These materials have potential applications in fields such as magnetic storage, sensing, and spintronic devices.[49]

3.4. Elemental Analysis

Elemental analysis is a crucial technique in chemistry, especially in the characterization of metal complexes. It involves determining the elemental composition of a compound, offering essential insights into the stoichiometry and molecular formula of synthesized complexes. By analyzing the amounts of various elements—typically carbon, hydrogen, nitrogen, and the metal content—researchers can confirm successful synthesis and ensure proper characterization of metal-ligand complexes. Several techniques are employed for elemental analysis, including combustion analysis, inductively coupled plasma mass spectrometry (ICP-MS), X-ray fluorescence (XRF), and energy dispersive X-ray spectroscopy (EDX). Combustion analysis is commonly used for organic compounds, where elements like carbon, hydrogen, and nitrogen are converted into their respective gaseous forms and analyzed. ICP-MS, highly sensitive, detects trace levels of metals by ionizing the sample and analyzing the ions via mass spectrometry. XRF measures the fluorescent X-rays emitted from a sample when excited by an X-ray source, and EDX, often paired with scanning electron microscopy, bombards samples with electrons to emit X-rays characteristic of the present elements.

Elemental analysis provides valuable information about the stoichiometry of metal-ligand complexes, allowing researchers to determine molar ratios between metal ions and ligands, which is critical for understanding the complex's stability and reactivity. It also confirms the molecular formula by comparing observed elemental ratios with theoretical ones, identifying any discrepancies that may indicate synthesis issues or impurities. Additionally, it acts as a quality control measure, ensuring the correct composition of synthesized complexes, which is vital for applications like pharmaceuticals, where compound purity is essential for safety and efficacy.

The applications of elemental analysis are broad, particularly in the study and characterization of metal complexes. It helps verify the presence of metal ions and ligands, contributing to understanding their structural and electronic properties. The stoichiometric data can also be used to determine stability constants of metal-ligand complexes, aiding in the analysis of equilibrium constants and complex behavior in solution. During synthesis, elemental analysis offers insights into reaction efficiency and product yield, helping optimize reaction conditions for better results. It also plays a role in studying reaction mechanisms by tracking changes in elemental composition, offering insights into pathways and intermediates in complex formation. In environmental chemistry, elemental analysis assesses heavy metal contamination levels in soils, waters, and sediments, crucial for environmental monitoring and remediation efforts. In materials science, it helps tailor the properties of metal-organic frameworks (MOFs) and coordination polymers for applications such as gas storage and catalysis.[50]

3.5. Thermal Analysis

Thermogravimetric Analysis (TGA) is a powerful analytical technique used to assess the thermal stability and decomposition characteristics of materials, particularly metal complexes. By measuring the change in weight of a sample as it is subjected to controlled heating, cooling, or isothermal conditions, TGA provides critical insights into the thermal behavior of compounds. The fundamental principle of TGA involves continuously monitoring a sample's weight as it is heated or cooled in a controlled atmosphere. A small, accurately weighed sample is placed in a balance within a furnace, where it is subjected to a predetermined temperature program, and the system records the weight changes as a function of temperature or time, producing a thermogravimetric curve. Typically, the sample is heated at a constant rate up to a specified temperature, where it may be cooled back down to room temperature. The atmosphere in the TGA chamber can be inert (e.g., nitrogen or argon) or reactive (e.g., air or oxygen), depending on the material being analyzed. Weight changes are plotted against temperature or time, and significant weight changes correlate with specific thermal events like dehydration, decomposition, or oxidation.

TGA provides valuable information about the thermal properties of metal complexes, including their thermal stability, decomposition temperatures, weight loss profiles, and residual mass. By analyzing the temperature at which significant weight loss occurs, researchers can assess the stability of a complex under thermal conditions. Higher decomposition temperatures typically indicate greater thermal stability, which is desirable in applications such as catalysis and materials science. TGA can also identify specific decomposition temperatures associated with different components of a complex, providing insights into the interactions between the metal and ligands and the stability of each component. The weight loss profiles help quantify the amount of weight lost at various temperatures, determining the stoichiometry of decomposition products and identifying any intermediate phases. Additionally, TGA provides information on the final mass of the sample after heating, which often corresponds to the metal content after ligand decomposition. Kinetic parameters such as activation energies and reaction mechanisms can also be derived from TGA data, offering a deeper understanding of the stability and reactivity of metal complexes under thermal stress.

TGA has a wide range of applications, particularly in the characterization of metal-ligand complexes. It is routinely used to determine the thermal stability and decomposition patterns of these complexes, helping researchers elucidate the interactions between metals and ligands. TGA is also a valuable tool for quality control during the synthesis of metal complexes, ensuring that the desired products are obtained without contamination. In catalysis, TGA helps assess the stability of metal complexes under varying thermal conditions, optimizing their performance and longevity in catalytic reactions. In materials science, TGA evaluates the thermal stability of polymeric materials, composites, and nanomaterials that incorporate metal complexes, which is crucial for applications in coatings, drug delivery systems, and advanced materials. In the pharmaceutical field, TGA is used to assess the stability of drug-metal complex formulations, informing storage conditions and shelf life. In environmental studies, TGA evaluates the thermal stability of metal complexes in soils, sediments, or wastewater treatments, providing important information for assessing the fate of metal contaminants and their potential environmental risks.[51]

Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) is a widely used thermal analysis technique that measures heat flow associated with transitions in materials as a function of temperature. It plays a crucial role in the characterization of materials, particularly in understanding the thermal properties and stability of metal complexes. By analyzing heat flow variations during controlled heating or cooling, DSC provides valuable insights into phase transitions, such as melting, crystallization, and glass transitions, which are essential for evaluating the performance and applicability of various compounds.

The principle of DSC involves comparing the heat flow into a sample with that of a reference material as both are subjected to a temperature program. A small amount of the sample material is placed in a pan, which is compared to an empty reference pan. Both pans are subjected to the same temperature conditions, and the instrument precisely controls the temperature of both the sample and reference pans, typically using a linear heating or cooling rate. Heat flow is measured as the temperature changes, and any heat absorbed or released by the sample during transitions, such as melting or crystallization, is detected as a difference in temperature between the sample and reference. The resulting data is plotted as a DSC curve, displaying heat flow versus temperature. Exothermic processes, such as crystallization, result in a downward peak on the DSC curve, while endothermic processes, such as melting, result in an upward peak. The area under these peaks is directly related to the amount of heat absorbed or released during the thermal transitions.

DSC provides several critical pieces of information regarding the thermal properties of materials, particularly metal complexes. It effectively determines melting points and other thermal transitions by identifying significant changes in the DSC curve that correlate with phase changes in the material. The technique also evaluates the heat capacity of the material, quantifying the amount of heat required to raise the temperature by one degree Celsius. This information is crucial for understanding thermal management and energy requirements in applications involving metal complexes. Furthermore, DSC provides information on enthalpy changes associated with phase transitions, such as fusion or crystallization. The area under the peaks in the DSC curve represents the enthalpy change, which is essential for evaluating the thermodynamic stability of metal complexes. This information can be used to calculate reaction enthalpies, Gibbs free energy, and other thermodynamic parameters. DSC can also identify glass transition temperatures in certain materials, especially polymers and organometallic complexes. This transition reflects a change in the physical state and is crucial for understanding the material's mechanical properties. Additionally, DSC data can indicate the thermal stability of metal complexes by identifying decomposition temperatures and thermal events that suggest instability.

The applications of DSC are extensive, particularly in the characterization of metal complexes and related materials. DSC is routinely used to study the thermal behavior of metal complexes by analyzing melting points, heat capacities, and enthalpy changes, providing insights into their stability and reactivity. In pharmaceutical research, DSC is utilized to analyze drug-metal complex interactions, helping to evaluate their compatibility, solubility, and release profiles in drug delivery systems. In materials science, DSC is essential for characterizing polymers, composites, and nanomaterials containing metal complexes. Understanding thermal transitions and stability informs the design of new materials with desired thermal properties for applications such as coatings and electronics. DSC is also employed in quality control during the synthesis and production of metal complexes, ensuring consistency in product quality and performance. Additionally, in research and development, DSC helps in developing new metal complexes with tailored properties by systematically studying the thermal behavior of various ligand and metal combinations. In environmental studies, DSC is used to assess the thermal behavior of metal complexes, providing vital information on their fate and transport in ecosystems.**[52]**

3.6. Mass Spectrometry

Mass spectrometry (MS) is a powerful analytical technique used to determine the mass-to-charge (m/z) ratio of ions, playing a crucial role in characterizing chemical compounds, including metal complexes. It provides valuable information about molecular weight, structure, and purity, and its ability to analyze complex mixtures and detect low-abundance species makes it indispensable in fields like chemistry, biochemistry, environmental science, and materials science. The principle of MS involves converting chemical species into ions, which are then separated based on their m/z ratios. The process includes ionization, where sample molecules are ionized using methods such as electrospray ionization (ESI), which generates ions by spraying the analyte in a fine mist, or matrix-assisted laser desorption/ionization (MALDI), where the sample is mixed with a matrix and irradiated with a laser. After ionization, the ions are accelerated by an electric field into a mass analyzer, where they are separated based on their m/z ratios. Common mass analyzers include quadrupole mass filters, which use oscillating electric fields to filter ions, time-of-flight (TOF) analyzers that measure ion travel time, and Orbitrap analyzers that use electric fields to trap ions for high-resolution measurements. Once separated, ions are detected, often by an electron multiplier that converts the ions into an electrical signal, which is then plotted as a mass spectrum displaying intensity versus m/z ratio.

Mass spectrometry provides critical information about metal complexes, including molecular weight and identity, allowing researchers to confirm the successful synthesis of a compound by analyzing m/z ratios. MS also offers structural information through fragmentation patterns that provide insights into how ligands are coordinated to the metal center and the presence of specific functional groups. Additionally, isotope patterns in MS can detect isotopic variations, aiding in the identification of isotopes such as ^13C or ^15N, which is useful for tracing the origin of materials. The purity of synthesized metal complexes can also be assessed using MS by analyzing the mass spectrum for unexpected peaks, where a clean spectrum with only the expected molecular weight indicates high purity. Furthermore, MS can be used for quantitative analysis, allowing researchers to determine the concentration of a complex by comparing ion signal intensities to standards.

The applications of mass spectrometry are vast. It is commonly employed to characterize newly synthesized metal complexes by confirming their molecular weight, identity, and structure. In biological studies, MS is used to analyze metal complexes involved in biological processes, such as metalloproteins, providing insights into their functions. Environmental analysis benefits from MS as well, as it helps detect metal pollutants in water, soil, and biological tissues. In pharmaceutical research, MS is utilized to study metal-based drugs, providing essential data on their pharmacokinetics and metabolism, aiding the development of therapeutic agents. MS is also critical in quality control during the synthesis and production of metal complexes in industrial settings, ensuring product consistency by assessing purity. Lastly, MS is increasingly applied in forensic science, where it is used to analyze metal-containing evidence, such as trace metals in biological samples, aiding in identifying sources or pathways of exposure.[53]

3.7. Electrochemical Techniques

Cyclic voltammetry (CV) is a powerful electrochemical technique widely used to study the redox properties of chemical species, especially metal complexes. This method provides valuable insights into electron transfer processes and plays a crucial role in characterizing the electrochemical behavior of various compounds. By controlling the potential of a working electrode, CV enables the investigation of the kinetics and thermodynamics of redox reactions, making it an essential tool in fields like analytical chemistry, materials science, and electrochemistry. In CV, the current response of an electrochemical system is measured as the potential of a working electrode is varied in a cyclic manner. A typical CV setup consists of a three-electrode system: a working electrode (where redox reactions occur), a reference electrode (to control the working electrode's potential), and a counter electrode (to complete the circuit). Common materials for these electrodes include glassy carbon, gold, or platinum. During the experiment, the potential of the working electrode is swept between two values (anodic and cathodic) at a set scan rate while the resulting current is monitored. After reaching the maximum potential, the potential is reversed, and the current is measured as it returns to the starting value, allowing for the examination of both oxidation and reduction reactions. The current-potential data are plotted as a cyclic voltammogram, which displays peaks corresponding to the redox processes of the analyte.

CV provides critical information for characterizing metal complexes. It allows the determination of redox potentials by identifying the positions of the anodic (oxidation) and cathodic (reduction) peaks, which reflect the thermodynamic favorability of the reactions. The shape and separation of these peaks indicate the reversibility of electron transfer processes, where reversible reactions show well-defined peaks with small separations (less than 60 mV), while irreversible reactions exhibit larger separations or may show only one peak. The peak current in a cyclic voltammogram can be used to study the kinetics of electron transfer processes, and the relationship between peak current and scan rate helps calculate diffusion coefficients. This information is key to understanding the speed and mechanisms of redox reactions. Additionally, the thermodynamic parameters, such as standard reduction potential (E°), can be extracted from the voltammogram, offering insights into the stability of metal complexes and the driving forces behind their redox behavior. CV also allows researchers to examine how different ligands affect the electrochemical properties of metal complexes by analyzing changes in peak positions and currents, which can indicate variations in ligand field strength and coordination around the metal ion.

Cyclic voltammetry has wide-ranging applications, particularly in the characterization of metal complexes. It is used to investigate the redox properties of newly synthesized metal complexes, confirming their oxidation states and stability in solution. In catalysis, CV helps evaluate the electrocatalytic activity of metal complexes for reactions such as oxygen reduction, hydrogen evolution, and organic transformations. The kinetic data from CV are crucial for understanding catalytic mechanisms and efficiencies. CV is also employed in the development of electrochemical sensors, where specific metal complexes are attached to electrode surfaces to create sensors that selectively detect metal ions or other analytes, making it useful in environmental monitoring and clinical diagnostics. In energy storage research, CV is applied to study redox-active materials used in batteries and supercapacitors, aiding in the development of more efficient energy devices. In corrosion studies, CV helps investigate the electrochemical behavior of metals and alloys, providing insights into corrosion mechanisms and strategies for material protection. Additionally, CV is valuable in biochemical applications, where it is used to study biomolecules and their interactions with metal complexes, offering insights into the redox properties of metalloproteins and enzyme systems, which are crucial for understanding their functions in biological processes.[54]

IV. APPLICATIONS OF METAL COMPLEXES

Here are some biological applications and general applications of Zinc(II), Mercury(II), and Iron(III) complexes.

4.1 Applications of Zinc(II) Complexes

Zinc(II) complexes are widely used in various fields due to their unique coordination chemistry. They serve as catalysts in organic synthesis, play a crucial role in biological systems (such as enzyme functions), and are used in material science for developing sensors and luminescent materials.

4.1.1 Biological Applications Of Zinc(II) Complexes

Zinc(II) complexes are essential in biological systems, functioning as active sites in enzymes like carbonic anhydrase and metalloproteinases. They have antibacterial, antifungal, antimicrobial and antioxidant activites. They also play roles in DNA synthesis, gene expression, and immune system regulation, making them critical for various physiological processes.

4.1.1.a) Antibacterial Activity Evaluation

An in vitro approach was used for antibacterial testing. All compounds and their metal complexes were tested against numerous bacterial strains, including Gram-positive (Pseudomonas aeruginosa) and Gram-negative (Escherichia coli, Staphylococcus aureus), using the well diffusion technique. Injection in nutritious broth (10 mL aliquot) and incubation for 24 hours at 37°C ± 1°C. The positive control was tetracycline (30 g disc), while the negative control was methanol. For greater diffusion, the petri plates were left at room temperature for two hours. Petri plates were incubated for 24 hours at 37°C ± 1°C.[55]

Table 1: Antibacterial Activity of Ligands and Their Metal Complexes (Zone of Inhibition (in mm))

Compound	E. Coli	Pseudomonas Aeruginosa	Staphylococcus Aureus
$(L1)_2Zn(Ac)_2$	11	20	11
$(L2)_2Zn(Ac)_2$	19	16	15
Reference Drug (Tetracycline)	25	20	23

4.1.1.b) Antifungal Activity Evaluation

The antifungal activity of the test compounds was assessed using two fungal strains: *Candida albicans* (C. albicans) and *Candida glabrata* (C. glabrata). The fungi were inoculated in Sabouraud dextrose broth (SDB) and incubated for 24 hours at 28°C. After incubation, the concentration of the test organisms was matched to the 0.5 McFarland standard.

For antifungal screening, the well-in-agar technique was employed. A sterile cotton swab was used to load the fungal culture, ensuring excessive inoculum removal by pressing the swab against the inside wall of the tube. The swab was then used to streak the fungal cultures onto the entire surface of sterile Sabouraud dextrose agar medium, rotating the plate approximately 60° each time to ensure even distribution. Using a sterile cork borer, holes of 6 mm diameter were bored into the inoculated medium, and each hole was labeled appropriately. Fifty microliters (50 µL) of the test samples (at a concentration of 1 mg/mL) were added to each hole. The standard drug used for comparison was Nystatin, while methanol served as the negative control.

The agar plates were sealed with parafilm and incubated at room temperature for an hour to improve the penetration of the test samples and reference medication. After that, the plates were incubated for 48 hours at 28°C. The appearance of inhibitory zones around the holes indicated antifungal activity.[56]

4.1.1.c) Antioxidant Activity Evaluation

The antioxidant activity of the test compounds was evaluated using the DPPH (2,2-diphenyl-2-picrylhydrazyl hydrate) assay. This method demonstrated the ability of the test compounds to scavenge free radicals through spectrophotometry against the stable free radical DPPH. The antioxidant moiety donates hydrogen, reducing DPPH and resulting in a color change from dark purple to yellow in methanol.

Final concentrations of the test samples were prepared at 500 µg/mL, 100 µg/mL, 50 µg/mL, 10 µg/mL, and 5 µg/mL, diluted from a stock solution of 1 mg/mL. Three milliliters (3 mL) of the sample solution dissolved in 5% DMSO were added to 1 mL of methanolic DPPH solution (0.3 mM). The mixture was vigorously mixed and allowed to sit at room temperature in the dark for 30 minutes. Absorbance was measured at 517 nm using a UV-VIS spectrophotometer. A lower absorbance indicated a higher free-radical scavenging action. Ascorbic acid was used as the standard, and methanol was used as the solvent.[57]

The radical scavenging action of DPPH was calculated using the following equation:

$$\textbf{scavenging effect}(\%) = \frac{\textbf{absorbance of control} - \textbf{absorbance of sample}}{\textbf{absorbance of control}} \times \mathbf{100}$$

Table 2: The Antifungal Action of Ligands and Their Metal Complexes

Compound	Zone of Inhibition(mm)	
	Candida Albican	Candida Glabrata
(L1)2Zn(Ac)2	20	<10
(L2)2Zn(Ac)2	13	10.5

4.1.1.d) Cytotoxicity Assays

The brine-shrimp microwell cytotoxicity assay was conducted using a simulated saltwater solution prepared by dissolving 38 grams of non-ionized NaCl in 1 liter of sterile distilled water. The solution was filtered to achieve clarity. To maintain the pH of the seawater between 8 and 9, a $NaHCO_3$ solution was added.

Brine shrimp eggs, scientifically known as *Artemia salina*, were acquired from a pet shop. A small tank, designed with a divider, was utilized for the experiment. Simulated seawater was poured into the tank, and 1.5 grams of shrimp eggs per liter were added to one side, which was then covered with aluminum foil. The eggs were allowed to hatch for 48 hours, resulting in mature nauplii (larvae). Throughout the hatching process, oxygen supply was maintained to ensure optimal conditions. The mature nauplii swam through the perforated divider toward the light source at the opposite end of the tank, and these nauplii were used for the bioassay.

Test samples were prepared in artificial seawater at concentrations of 1000 µg/mL, 500 µg/mL, 100 µg/mL, 50 µg/mL, 10 µg/mL, and 5 µg/mL. Water-insoluble compounds were dissolved in 5% DMSO before being mixed with the saltwater. To establish negative and positive controls, constant amounts of DMSO and doxorubicin were included in the experiment.

In a 96-well microplate, each concentration of the test samples was added in triplicate. Ten brine shrimp larvae were placed in each well along with the various concentrations and saltwater. The microplate was then covered and incubated at a warm temperature ranging from 22°C to 29°C for 24 hours. After the incubation period, the nauplii were examined under a microscope or magnifying glass, and the number of dead (non-mobile) larvae was recorded for each well[58].

4.1.1.e) Antimicrobial Activity

Zinc(II) complexes have emerged as significant players in the quest for novel antimicrobial agents, exhibiting potent antibacterial and antifungal properties. This interest is largely attributed to their unique mechanisms of action and the versatile nature of the ligand frameworks that can be employed in their synthesis. Unlike traditional antibiotics, zinc(II) complexes present a multifaceted approach to combatting pathogenic microorganisms, providing a much-needed alternative in an era marked by rising antibiotic resistance.

The antimicrobial efficacy of zinc(II) complexes is primarily rooted in their ability to interact with microbial cells in ways that disrupt normal cellular function. One of the primary mechanisms involves the disruption of microbial cell membranes. Zinc ions can interact with phospholipids and proteins within the cell membrane, leading to increased permeability. This disruption not only compromises the integrity of the microbial cell but can also lead to cell lysis, ultimately resulting in the death of the microorganism. Additionally, zinc ions are known to interfere with various metabolic processes essential for microbial growth and replication. By inhibiting enzymatic activity and disrupting nucleic acid synthesis, zinc(II) complexes hinder the ability of pathogens to multiply, thereby contributing to their antibacterial and antifungal actions.

The adaptability of Schiff base ligands is particularly noteworthy in the development of zinc(II) complexes. These ligands can be engineered with specific electronic and steric properties to optimize the interaction with microbial targets. The ability to fine-tune these properties allows researchers to create zinc(II) complexes that are not only more effective against a broad spectrum of microorganisms but can also be tailored for specific applications. For instance, the incorporation of lipophilic groups into the ligand structure enhances the hydrophobicity of the complex, which can facilitate its passage across lipid membranes and improve its bioavailability within microbial cells.

As the prevalence of multidrug-resistant infections continues to escalate, the need for new antimicrobial agents becomes increasingly urgent. Zinc(II) complexes stand out as promising candidates in this regard. Their unique mechanisms of action may prove effective against bacteria and fungi that have developed resistance to conventional treatments. Research has shown that certain zinc(II) complexes possess enhanced activity against antibiotic-resistant strains, making them invaluable tools in the fight against resistant infections.

Moreover, the clinical potential of zinc(II) complexes extends beyond their direct antimicrobial effects. Zinc is an essential trace element in human health, playing a critical role in immune function, wound healing, and cellular metabolism. This intrinsic connection to human physiology adds another layer of appeal to zinc(II) complexes, as they may possess additional therapeutic benefits when used in clinical settings.

The application of zinc(II) complexes as antifungal agents is equally promising. Fungal infections, particularly those caused by opportunistic pathogens, have become a significant concern, especially in immunocompromised individuals. The ability of zinc(II) complexes to disrupt fungal cell membranes and metabolic processes presents a viable strategy for managing these infections. Studies indicate that various zinc(II) complexes have shown remarkable efficacy against common fungal strains, including Candida species. This broad spectrum of activity underscores their potential for development into effective antifungal treatments.[59]

In the ongoing research on zinc(II) complexes, several studies have highlighted the enhanced antibacterial activity of these complexes compared to their free ligand counterparts. For instance, zinc(II) complexes have been found to exhibit greater inhibitory effects on both gram-positive and gram-negative bacteria, including notorious pathogens such as Escherichia coli and Staphylococcus aureus. The superior activity of these complexes can often be attributed to the chelation of the zinc ion, which alters its physicochemical properties, enhancing its interaction with microbial cells.

Moreover, specific modifications to the ligand structure can significantly influence the biological activity of zinc(II) complexes. For example, the introduction of electron-withdrawing groups can enhance the complex's ability to penetrate bacterial membranes, thereby increasing its efficacy. Research has shown that the presence of nitro groups in the ligand framework often correlates with improved antimicrobial activity.[60]

The variety of ligands used in the synthesis of zinc(II) complexes, such as those derived from salicylaldehyde or other aromatic aldehydes, has demonstrated that the structural diversity of these complexes contributes to their potent bioactivity. The incorporation of different functional groups can lead to complexes that are not only effective but also exhibit selectivity towards particular bacterial strains or fungi.

In addition to their direct antimicrobial properties, zinc(II) complexes have shown promise in synergistic applications with existing antibiotics. When used in conjunction with traditional antimicrobial agents, these complexes can enhance the overall effectiveness of treatment regimens, potentially reducing the required dosages and minimizing the risk of side effects.

The future of zinc(II) complexes in antimicrobial therapy is bright, given the ongoing research and development efforts focused on these compounds. Their potential as alternatives or adjuncts to traditional antimicrobial agents positions them as crucial players in the fight against infectious diseases. As the scientific community continues to explore the myriad possibilities of zinc(II) complexes, we may witness the emergence of innovative therapeutic strategies that leverage their unique properties to address the pressing challenges of antimicrobial resistance and the need for effective treatments against infections.[61]

Overall, the antimicrobial activity of zinc(II) complexes represents a significant area of research that holds promise for enhancing our arsenal against infectious diseases. By understanding their mechanisms of action and exploring their structural diversity, we can develop effective treatments that not only target resistant strains of bacteria and fungi but also support human health through the beneficial roles of zinc in biological systems.

4.1.1.f) Enzyme Mimics

Zinc ions (Zn^{2+}) are crucial for the catalytic activity of numerous enzymes, such as metalloproteases, dehydrogenases, and carbonic anhydrases. Zinc's unique properties—including its ability to adopt multiple coordination geometries, form stable complexes, and participate in electron transfer reactions—make it an ideal cofactor. In enzymes, zinc's coordination with histidine, cysteine, and other amino acids in the active site facilitates substrate binding, stabilizes transition states, and participates in redox reactions. For instance, in carbonic anhydrases, zinc ions are coordinated to three histidine residues and a water molecule, enabling the enzyme to catalyze the efficient interconversion of carbon dioxide and bicarbonate. Zinc not only enhances the enzyme's catalytic activity but also contributes to its structural integrity, underscoring its vital role in enzymatic functions and highlighting the potential of zinc(II) complexes as enzyme mimics.[62]

Zinc(II) complexes, formed through the coordination of zinc ions with organic ligands, effectively mimic the behavior of natural enzymes. These complexes replicate catalytic functions by stabilizing substrates, facilitating reaction pathways, and influencing enzyme kinetics. As enzyme mimics, zinc(II) complexes serve as valuable tools for studying enzymatic mechanisms and developing synthetic catalysts. The catalytic activity of zinc(II) complexes is largely attributed to the metal center's coordination environment and electronic properties. Zinc(II) complexes can catalyze hydrolytic reactions similar to metalloenzymes, and researchers have synthesized various zinc(II) complexes with ligands that mimic active sites of enzymes like phosphatases and hydrolases. For example, zinc(II) complexes of salicylaldehyde-derived ligands have demonstrated the ability to catalyze the hydrolysis of phosphoester bonds, with the zinc center enhancing the electrophilicity of the phosphorus atom and facilitating nucleophilic attack by water molecules. This behavior offers insights into the mechanisms of phosphatase enzymes, which are critical in cellular signaling and metabolism.

The structural diversity of zinc(II) complexes allows for the exploration of their catalytic properties. By modifying ligand structures, researchers can optimize the electronic and steric factors that influence catalytic activity. Variations in donor atoms, such as nitrogen or sulfur, can alter the coordination geometry around the zinc ion, modulating its reactivity. Ligands with different functional groups, such as hydrophobic or electron-withdrawing groups, can improve substrate binding and enhance catalysis. Understanding these structure-activity relationships enables the design of more efficient enzyme mimics and opens up new applications in biocatalysis.[63]

In addition to acting as enzyme mimics, zinc(II) complexes can serve as inhibitors of zinc-dependent enzymes, providing insights into the regulation of enzymatic pathways and offering potential leads for drug development. By competitively or non-competitively binding to the active site, zinc(II) complexes can inhibit enzyme activity. For instance, zinc(II) complexes have been developed as inhibitors of carbonic anhydrases, enzymes involved in processes such as acid-base balance and respiratory function. The design of these inhibitors focuses on optimizing ligand structures to achieve specific interactions with the enzyme's active site. Through studies of inhibition kinetics and binding modes, researchers can deepen their understanding of enzyme regulation and identify therapeutic targets for diseases associated with dysregulated zinc-dependent enzymes.[64]

4.1.1.g) Applications in Biochemical Studies

Zinc(II) complexes, due to their versatile biochemical properties, have shown potential for a wide range of applications beyond basic research, extending into drug discovery, biomimetic catalysis, and environmental remediation. In the field of drug discovery, zinc(II) complexes hold promise as enzyme inhibitors, particularly for targeting zinc-dependent enzymes that play critical roles in disease pathways. Researchers have explored the potential of zinc(II) complexes to modulate enzymatic activity, offering new therapeutic strategies for diseases such as cancer, diabetes, and neurodegenerative disorders. For instance, zinc-dependent matrix metalloproteinases (MMPs) are involved in the remodeling of the extracellular matrix, a process that is often dysregulated in cancer progression. By designing zinc(II) complexes as inhibitors of MMPs, researchers have identified promising lead compounds for cancer therapy, with the goal of limiting tumor growth and metastasis. The ability to inhibit other zinc-dependent enzymes also opens the door to therapeutic approaches for diseases that are influenced by enzymatic dysregulation, such as metabolic disorders and neurodegenerative conditions.[65]

In biomimetic catalysis, zinc(II) complexes have gained attention for their role as synthetic catalysts that can replicate the catalytic functions of natural enzymes. By mimicking enzymatic reactions, these complexes enable the development of efficient and sustainable methods for organic synthesis. Zinc(II) complexes have demonstrated the ability to catalyze key organic transformations, including the formation of carbon-carbon (C–C) and carbon-nitrogen (C–N) bonds, which are fundamental to the synthesis of a wide range of chemical compounds. The ability of zinc(II) complexes to replicate the specificity and efficiency of natural enzymes presents exciting opportunities for the design of environmentally friendly catalytic processes. These synthetic methods not only reduce the need for harsh chemicals and reaction conditions but also align with the growing demand for greener chemistry solutions in industrial applications.

Zinc(II) complexes also hold potential in environmental remediation, particularly through their ability to mimic the functions of zinc-dependent enzymes involved in the breakdown of environmental pollutants. Certain natural enzymes, which depend on zinc for their activity, are capable of degrading harmful substances such as pesticides and heavy metals. By designing zinc(II) complexes that replicate these enzymatic processes, researchers aim to develop new strategies for bioremediation, enabling more efficient cleanup of contaminated environments. The ability of zinc(II) complexes to enhance the degradation rates of pollutants makes them valuable tools for addressing environmental challenges, such as the detoxification of soil and water sources affected by industrial waste.[66]

In addition to these applications, zinc(II) complexes have gained recognition for their antioxidant properties, which have significant implications for human health, particularly in the context of diseases related to oxidative stress. Oxidative stress arises from an imbalance between the production of reactive oxygen species (ROS) and the body’s capacity to neutralize them or repair the resulting damage. Excessive levels of ROS, such as free radicals like superoxide and hydroxyl radicals, as well as non-radical species like hydrogen peroxide, can cause oxidative damage to cellular components, including lipids, proteins, and DNA. This damage contributes to the development of a wide range of diseases, including cancer, cardiovascular diseases, neurodegenerative disorders, and the aging process. Antioxidants play a vital role in neutralizing ROS, thereby protecting cells from oxidative damage and preserving cellular function.

Zinc, an essential trace element, is involved in several biological processes, including enzymatic reactions, protein synthesis, and gene expression. Beyond its function as a cofactor for numerous enzymes, zinc is also known for its antioxidant properties, contributing to cellular protection through various mechanisms. Zinc ions (Zn^{2+}) can directly scavenge ROS, lowering their concentrations and preventing oxidative damage to cellular components. Additionally, zinc acts as a cofactor for antioxidant enzymes like superoxide dismutase (SOD), which catalyzes the conversion of superoxide radicals into less harmful molecules like hydrogen peroxide and oxygen. This enzymatic activity is crucial for detoxifying ROS and maintaining cellular homeostasis. Zinc also stabilizes the structure of antioxidant proteins, prolonging their functional lifespan and enhancing their activity, especially under conditions of oxidative stress.

Zinc(II) complexes, formed through the coordination of zinc ions with various ligands, exhibit enhanced antioxidant properties compared to free zinc ions. These enhanced properties can be attributed to the specific coordination environment around the zinc ion, which influences its reactivity with ROS, as well as the nature of the ligands coordinated to the zinc ion. Ligands that possess electron-donating groups or inherent antioxidant properties can significantly improve the ROS-scavenging abilities of the zinc(II) complex. Additionally, zinc(II) complexes with greater lipophilicity tend to have improved cellular uptake, increasing intracellular zinc concentrations and thereby amplifying the complex’s antioxidant effects.

The antioxidant mechanisms of zinc(II) complexes are varied. These complexes can neutralize free radicals by reacting with ROS, preventing oxidative damage to lipids, proteins, and DNA. Moreover, zinc(II) complexes can modulate signaling pathways associated with oxidative stress, influencing the expression and activity of antioxidant enzymes. For example, they can activate the Nrf2/ARE signaling pathway, which upregulates the expression of cytoprotective genes involved in the body’s antioxidant defense systems. Zinc(II) complexes also inhibit lipid peroxidation, a damaging consequence of oxidative stress that leads to the destruction of cell membranes and ultimately cell death. By scavenging lipid radicals and stabilizing membrane structures, zinc(II) complexes prevent this destructive process and help preserve cellular integrity. The antioxidant properties of zinc(II) complexes have promising implications for disease prevention and treatment, particularly for conditions associated with oxidative stress. In neurodegenerative diseases like Alzheimer’s and Parkinson’s, zinc(II) complexes can protect neuronal cells from oxidative damage, offering a potential therapeutic approach to prevent or slow the progression of these disorders. Their ability to modulate neuroinflammatory responses and enhance neuronal survival adds to their therapeutic value. In cardiovascular health, zinc(II) complexes can protect endothelial cells from oxidative damage, improve endothelial function, and reduce inflammation, which may lower the risk of cardiovascular complications such as atherosclerosis. Additionally, zinc(II) complexes have potential applications in cancer therapy, where they can increase oxidative stress selectively in cancer cells, leading to apoptosis (programmed cell death). By modulating redox-sensitive signaling pathways, zinc(II) complexes can further enhance the efficacy of chemotherapeutic agents, making them valuable as adjuvants in cancer treatment. Moreover, their antioxidant properties may also help mitigate age-related oxidative damage, promoting healthy aging and longevity by bolstering the body's defense mechanisms against oxidative stress[67].

4.1.1.g.i) Drug Discovery

The development of zinc(II) complexes as enzyme inhibitors has significant implications for drug discovery. By targeting zinc-dependent enzymes, researchers can design compounds that modulate enzymatic activity, offering new therapeutic strategies for diseases such as cancer, diabetes, and neurodegenerative disorders. For instance, inhibitors of matrix metalloproteinases (MMPs), which are zinc-dependent enzymes involved in extracellular matrix remodeling, have shown potential in cancer therapy. Zinc(II) complexes can serve as lead compounds in this context, facilitating the identification of novel drug candidates.[68]

4.1.1.g.ii) Environmental Remediation

Zinc(II) complexes can play a role in environmental remediation by mimicking enzymes involved in bioremediation processes. For example, certain zinc-dependent enzymes are responsible for the degradation of pollutants such as pesticides and heavy metals. By designing zinc(II) complexes that replicate these enzymatic functions, researchers can explore new strategies for the bioremediation of contaminated environments. These complexes can enhance the degradation rates of pollutants, providing an efficient approach to environmental clean-up.

Zinc(II) complexes have emerged as promising antioxidants, protecting cells from oxidative stress, which is linked to diseases like cancer, cardiovascular disorders, neurodegeneration, and aging. These complexes scavenge reactive oxygen species (ROS) and enhance the activity of antioxidant enzymes like superoxide dismutase (SOD). By modulating pathways such as Nrf2/ARE and inhibiting lipid peroxidation, zinc(II) complexes strengthen cellular defenses against oxidative damage. Their therapeutic potential extends to neurodegenerative diseases, cardiovascular health, and cancer therapy, where they enhance oxidative stress in cancer cells and support the effectiveness of treatments, promoting longevity and healthy aging.[69]

4.1.1.g.iii) Therapeutic Agents

Cancer remains one of the leading causes of mortality worldwide, presenting significant challenges in treatment and management. Traditional therapies, including chemotherapy and radiation, often face limitations due to resistance, toxicity, and adverse side effects. Consequently, there is a growing interest in exploring alternative therapeutic agents that can selectively target cancer cells while minimizing damage to normal tissues. Zinc complexes have emerged as promising candidates in this context, owing to their unique properties, including the ability to induce apoptosis in cancer cells. This article discusses the mechanisms through which zinc complexes exert their anticancer effects, their potential therapeutic applications, and the future directions for research in this field.

Zinc complexes exert their anticancer effects through multiple mechanisms, primarily by inducing apoptosis in cancer cells. One of the key ways they promote cell death is by enhancing the generation of reactive oxygen species (ROS) within cancer cells. Increased levels of ROS cause oxidative stress, overwhelming the cell's natural antioxidant defenses. This leads to the damage of essential cellular components such as lipids, proteins, and DNA. The resultant oxidative damage activates apoptotic signaling pathways, driving the cell toward programmed death. Studies have shown that certain zinc complexes significantly elevate ROS levels, making them potent inducers of apoptosis in various cancer cell lines.

Another important mechanism by which zinc complexes trigger apoptosis is through mitochondrial dysfunction. Mitochondria play a central role in regulating cell death, particularly in the intrinsic pathway of apoptosis. Zinc complexes can disrupt the mitochondrial membrane potential, leading to the release of cytochrome c from the mitochondria into the cytosol—a critical event that initiates the apoptotic cascade. In addition, zinc complexes can tip the balance toward apoptosis by activating pro-apoptotic proteins such as Bax, while inhibiting anti-apoptotic proteins like Bcl-2. This disruption in the delicate equilibrium between cell survival and death further promotes the apoptotic process.

Caspases, a family of protease enzymes, are essential executioners of apoptosis, and zinc complexes have been found to activate these enzymes. Specifically, caspase-3, one of the key executioner caspases, is often activated in cancer cells treated with zinc complexes. Once activated, caspases cleave a variety of cellular substrates, leading to the dismantling of the cell and its eventual death. The activation of these enzymes not only drives the apoptotic process but also enhances the overall efficacy of cancer therapy, particularly in combination with other treatments.

Zinc complexes also influence key signaling pathways involved in cell survival and apoptosis. One such pathway is the p53 pathway, a crucial regulator of the cell cycle and apoptosis. Zinc complexes can activate p53, which leads to cell cycle arrest and the induction of pro-apoptotic factors. This activation forces cancer cells into programmed death, reducing their capacity to proliferate. Furthermore, zinc complexes can modulate the NF-κB signaling pathway, which is often activated in cancer cells to promote their survival. By inhibiting NF-κB signaling, zinc complexes enhance apoptotic signaling and make cancer cells more susceptible to death, further enhancing their potential as anticancer agents.

In addition to inducing apoptosis, zinc complexes can also inhibit angiogenesis—the process of forming new blood vessels that is crucial for tumor growth and metastasis. Tumors require a steady blood supply to receive nutrients and oxygen for growth. Zinc complexes have been shown to reduce the expression of angiogenic factors such as vascular endothelial growth factor (VEGF), which is essential for blood vessel formation. By curbing angiogenesis, zinc complexes effectively reduce the blood supply to tumors, thereby hindering their growth and promoting apoptotic pathways. This multifaceted ability of zinc complexes to disrupt essential processes in cancer cells makes them valuable candidates in the development of novel cancer therapies.

Zinc complexes have emerged as promising candidates for cancer therapy due to their unique properties and mechanisms of action. Various studies have explored the potential of these complexes in treating different types of cancer, highlighting their ability to induce apoptosis, inhibit cell proliferation, and modulate key signaling pathways involved in cancer progression. In breast cancer, zinc complexes have demonstrated potent anticancer activity by inducing apoptosis and inhibiting the proliferation of cancer cells. Research has shown that these compounds elevate reactive oxygen species (ROS) levels, leading to oxidative stress that triggers apoptotic pathways. This dual mechanism not only hampers cancer cell growth but also enhances the sensitivity of breast cancer cells to other therapeutic interventions.

Similarly, prostate cancer has been another focus of zinc complex research. Zinc compounds have been reported to inhibit the growth of prostate cancer cells, induce cell death through apoptosis, and reduce the expression of oncogenes associated with cancer progression. These findings suggest that zinc complexes could serve as effective therapeutic agents in managing prostate cancer, either as standalone treatments or in combination with existing therapies. In the case of lung cancer, zinc complexes have shown potential by inducing apoptosis in lung cancer cell lines. In vitro studies reveal that these complexes increase ROS levels and activate caspases, key enzymes in the apoptotic process, which ultimately lead to cancer cell death.

Research on colorectal cancer has also indicated that zinc complexes are effective in inhibiting the growth of cancer cells. By modulating signaling pathways linked to cell survival and apoptosis, zinc complexes not only reduce cancer cell proliferation but also enhance the apoptotic response, which is crucial for controlling tumor growth. Additionally, zinc complexes have been studied in the context of leukemia, where their ability to induce apoptosis and inhibit cell proliferation in leukemic cells suggests a potential role in treating blood cancers. These findings underscore the broad applicability of zinc complexes across various types of cancer.

However, despite the promising anticancer properties of zinc complexes, several challenges need to be addressed to fully realize their therapeutic potential. One major challenge is bioavailability, as the solubility and stability of zinc complexes can significantly impact their effectiveness in vivo. Researchers are currently exploring different formulations and drug delivery systems to improve the pharmacokinetics of zinc complexes, ensuring that they reach cancer cells in sufficient concentrations to exert their therapeutic effects. Another challenge is achieving selectivity, as it is crucial to target cancer cells while minimizing toxicity to normal cells. Understanding the specific mechanisms that confer selectivity to zinc complexes is essential for optimizing their design and reducing side effects in clinical applications.

Moreover, combining zinc complexes with existing cancer therapies, such as chemotherapy or targeted treatments, holds promise for enhancing their efficacy and overcoming drug resistance. Investigating the synergistic effects of such combination therapies and determining optimal dosing regimens is a key area of ongoing research. Finally, more preclinical and clinical studies are required to evaluate the safety and efficacy of zinc complexes in cancer therapy. Well-designed clinical trials will be instrumental in providing the necessary insights into the therapeutic potential of these compounds, paving the way for their eventual inclusion in cancer treatment protocols. While challenges remain, the unique anticancer mechanisms of zinc complexes, coupled with ongoing advancements in drug delivery and formulation, make them promising candidates for future cancer therapies.

The pharmaceutical industry faces a significant challenge with the increasing number of poorly soluble drugs, which limits their therapeutic effectiveness due to issues such as low bioavailability and poor absorption. This problem is particularly common with hydrophobic drugs that struggle to dissolve in biological fluids, leading to inconsistent absorption and diminished clinical outcomes. These solubility issues present a range of challenges, including inconsistent drug absorption, which results in fluctuating plasma concentrations and makes it difficult to achieve the therapeutic effect needed for optimal treatment. Additionally, to compensate for poor solubility, higher doses of drugs are often required, which increases the risk of side effects and toxicity. Traditional formulation strategies aimed at enhancing solubility are often insufficient, leaving pharmaceutical developers with limited options for improving the performance of these drugs. Moreover, drugs with low solubility frequently require complex dosing regimens, which can negatively impact patient compliance, as more cumbersome or frequent dosing schedules tend to reduce adherence to prescribed treatments.

To address these challenges, researchers are focusing on innovative drug delivery systems, with zinc complexes emerging as a promising solution for enhancing the solubility and bioavailability of poorly soluble compounds. Zinc complexes offer several advantageous properties that make them suitable for improving drug delivery. One of the key benefits of using zinc complexes is their ability to enhance solubility. Zinc ions can interact with poorly soluble drugs to form coordination complexes that increase drug dissolution rates in aqueous environments, thereby facilitating better absorption. By improving solubility, these zinc-based complexes can also significantly enhance the bioavailability of the drug, ensuring more consistent and effective therapeutic outcomes. This improvement in bioavailability allows for lower doses of the drug to be administered, minimizing the risk of adverse side effects and enhancing the overall safety of the treatment.

In addition to enhancing solubility and bioavailability, zinc complexes provide other valuable benefits, such as increased chemical stability. The formation of zinc complexes can stabilize drugs, protecting them from degradation during formulation and storage. This enhanced stability is critical for ensuring that the drug remains potent and effective throughout its shelf life. Furthermore, zinc complexes can be engineered to deliver controlled-release profiles, providing sustained drug delivery over a longer period. Controlled release systems are beneficial because they minimize fluctuations in drug plasma levels, reducing the need for frequent dosing and maintaining a more consistent therapeutic effect.

The mechanisms by which zinc complexes improve drug solubility and bioavailability are multifaceted. One such mechanism is through coordination chemistry, where zinc ions form complexes with various ligands, including poorly soluble drugs. This interaction alters the physical and chemical properties of the drug, enhancing its solubility in water and other aqueous environments. Additionally, zinc complexes can modulate the pH of the surrounding environment, which can influence the solubility of certain drugs. Some poorly soluble drugs exhibit increased solubility at specific pH levels, and zinc complexes help maintain those optimal conditions for better drug dissolution and absorption.

Another mechanism involves the formation of micelles, which are aggregates of surfactant molecules that can encapsulate hydrophobic drugs. Zinc complexes can promote the formation of these micelles, which improves the solubility of hydrophobic drugs in aqueous environments and enhances their absorption in the body. Furthermore, zinc complexes can also be employed in the formulation of nanoparticles, which serve as carriers for poorly soluble drugs. These nanoparticles can encapsulate the drug, increasing its solubility and providing targeted delivery to specific tissues or organs, thus improving bioavailability. Nanoparticles offer the added advantage of potentially reducing off-target effects and ensuring that the drug is delivered to the intended site of action with greater precision.

Despite the promising potential of zinc complexes in improving drug delivery, further research is needed to optimize their use in clinical settings. As the pharmaceutical landscape continues to evolve, zinc complexes could play a pivotal role in overcoming the solubility challenges associated with many modern drug candidates, ultimately leading to more effective treatments and improved patient outcomes. Researchers are exploring various approaches to enhance the efficacy of zinc complexes in drug delivery, including the development of novel formulations and advanced delivery systems. With ongoing innovation in this area, zinc complexes have the potential to revolutionize the way poorly soluble drugs are administered, addressing a critical need in the pharmaceutical industry.

The unique properties of zinc complexes make them suitable for various applications in drug delivery systems:

Oral Drug Delivery: Zinc complexes can enhance the solubility and bioavailability of orally administered drugs, particularly for poorly soluble compounds. For example, zinc-based formulations have been studied for their effectiveness in enhancing the absorption of nonsteroidal anti-inflammatory drugs (NSAIDs) and certain antibiotics.

Intravenous Drug Delivery: Zinc complexes can improve the solubility of injectable drugs, allowing for higher concentrations to be formulated. This application is particularly relevant for drugs that are poorly soluble in traditional solvents, enhancing their therapeutic efficacy.

Topical Drug Delivery: Zinc complexes can be incorporated into topical formulations to enhance the solubility and bioavailability of active pharmaceutical ingredients. For instance, zinc-based formulations have shown promise in improving the delivery of antifungal agents in dermatological applications.

Targeted Drug Delivery: The ability of zinc complexes to form nanoparticles or micelles can be exploited for targeted drug delivery. These formulations can enhance the accumulation of drugs in specific tissues, improving therapeutic outcomes while reducing systemic toxicity.

Combination Therapy: Zinc complexes can be utilized to improve the solubility and bioavailability of drugs used in combination therapies. For example, they can enhance the effectiveness of chemotherapeutic agents that exhibit poor solubility, allowing for better cancer treatment outcomes.

Challenges and Future Directions: While zinc complexes show great promise in drug delivery systems, several challenges remain that need to be addressed to fully harness their potential. One of the primary areas requiring attention is the optimization of formulations. This involves extensive research to determine the most effective combinations of zinc and drug molecules, as well as selecting the appropriate ligands and delivery systems. Achieving the right balance of these elements is crucial for maximizing the therapeutic benefits while ensuring that the drug is delivered efficiently to the target site. Additionally, the formulation needs to be tailored in such a way that it enhances drug solubility and bioavailability without compromising stability or efficacy. Factors such as the solubility of the complex, its dissolution rate, and the ability to sustain controlled release all play a critical role in the overall performance of the drug delivery system.

Biocompatibility and safety are other major considerations. While zinc is an essential element involved in various physiological processes, the introduction of zinc complexes in drug delivery requires careful evaluation of their safety profile. Long-term toxicity studies are essential to ensure that these complexes do not elicit adverse reactions in patients. It is important to assess how the body metabolizes and excretes these complexes, and whether their accumulation over time poses any risks. Thorough preclinical evaluations should be conducted to examine potential side effects, especially for prolonged or high-dose use, which could lead to zinc toxicity or other complications. Only after confirming that the complexes are safe for use can they be considered viable candidates for therapeutic application.[70]

Another challenge is navigating the regulatory landscape. The development of new drug delivery systems involving zinc complexes will require comprehensive regulatory approval, which can be a lengthy and complex process. Regulatory agencies require extensive documentation demonstrating the safety, efficacy, and stability of these formulations. This process often involves rigorous testing, including pharmacokinetic studies, toxicity assessments, and preclinical trials, all of which need to be meticulously documented. Gaining approval from regulatory bodies such as the U.S. Food and Drug Administration (FDA) or the European Medicines Agency (EMA) is essential for bringing these innovative therapies to market, but the path to commercialization can be fraught with regulatory hurdles that may slow down the development timeline.

Clinical studies will play a vital role in proving the efficacy of zinc complexes in improving the bioavailability of poorly soluble drugs. These trials need to be well-designed, involving diverse patient populations to ensure that the results are widely applicable. It is essential to evaluate how zinc complexes perform in different demographic groups, including variations in age, gender, genetic background, and existing health conditions. Such diversity in clinical testing will help researchers understand potential differences in patient response to these drug delivery systems and will be critical for determining the optimal therapeutic applications for zinc complexes. Additionally, these studies will need to compare the effectiveness of zinc complexes to existing drug delivery technologies to justify their use in clinical practice.

Looking toward the future, personalized medicine could offer exciting opportunities for the use of zinc complexes in drug delivery. The ability to tailor drug formulations to the individual needs of patients could significantly improve therapeutic outcomes, particularly for those with specific health conditions or genetic predispositions. Personalized formulations would allow for more precise control over drug dosage, release profiles, and bioavailability, enhancing the effectiveness of treatment while minimizing potential side effects. Further research is needed to explore how zinc complexes can be adapted to fit the emerging trend of personalized medicine, and how these complexes can be integrated into patient-specific therapies. The development of more advanced technologies, such as nanotechnology and precision medicine tools, will likely be key in this evolution.

In summary, while the potential of zinc complexes in drug delivery is immense, various challenges related to formulation optimization, safety, regulatory approval, and clinical validation must be overcome. With continued research and development, zinc complexes have the potential to revolutionize drug delivery systems, particularly for poorly soluble drugs, and pave the way for more effective and personalized treatments in the future.[71]

4.1.2. General Applications OF Zinc(II) complexes

4.1.2.a) Catalysis

Zinc(II) complexes have emerged as versatile catalysts in various chemical reactions due to their unique properties, including their ability to stabilize reaction intermediates, facilitate electron transfer, and participate in Lewis acid-base interactions. These complexes play a significant role in catalysis, particularly in organic reactions such as polymerization, oxidation processes, and carbon-carbon bond formation. Zinc(II) complexes are coordination compounds in which zinc ions (Zn^{2+}) are bound to various ligands, such as organic molecules, amino acids, or metal ions. The nature of these ligands can significantly influence the catalytic activity, selectivity, and stability of the zinc complex, with the electronic and steric properties of these compounds making them highly suitable for various catalytic applications in organic synthesis.

One of the most prominent roles of zinc(II) complexes in catalysis is their function as Lewis acids. In this capacity, zinc complexes facilitate nucleophilic attacks by stabilizing negative charges, a property particularly useful in reactions involving carbonyl compounds. For example, zinc(II) complexes activate the carbonyl carbon, making it more susceptible to nucleophilic attack, a mechanism widely utilized in aldol condensations and Michael additions. Additionally, zinc(II) complexes can serve as electron donors or acceptors, making them effective in oxidation-reduction (redox) reactions. They stabilize radical intermediates and promote electron transfer, which is crucial in transformations such as the oxidation of alcohols to carbonyl compounds or the reduction of ketones to alcohols. Zinc complexes can also coordinate with functional groups like hydroxyls or carboxyls, enhancing the reactivity of these groups. This coordination, for instance, allows the conversion of alcohols into more reactive species like alkyl halides or esters, simplifying synthetic pathways.

Zinc(II) complexes are particularly important in polymerization reactions. They play a crucial role in the coordination polymerization of olefins, where they help initiate and propagate polymer chains, leading to well-defined polymer structures. For instance, zinc complexes are employed in the production of polyolefins, facilitating the polymerization of ethylene and propylene into high-performance plastics. Additionally, zinc(II) complexes are used in the ring-opening polymerization of lactones and cyclic ethers, producing biodegradable polymers with tailored properties. This is especially significant in the development of sustainable materials.

In oxidative catalysis, zinc(II) complexes are highly effective in the selective oxidation of alcohols to aldehydes or ketones. These reactions often use oxidants like molecular oxygen or hydrogen peroxide, with zinc complexes facilitating the oxygen transfer to the substrate. Zinc complexes are also employed in the hydroxylation of aromatic compounds, introducing hydroxyl groups at specific positions, which is a critical step in the synthesis of pharmaceutical intermediates and agrochemicals.

Zinc(II) complexes are also involved in catalyzing carbon-carbon bond formation, a fundamental process in organic chemistry. These complexes are used in cross-coupling reactions, such as Suzuki and Negishi couplings, where zinc acts as a mediator that facilitates the coupling of organohalides with organometallic reagents, leading to the formation of carbon-carbon bonds. This method is highly versatile and allows for the synthesis of complex organic molecules, often used in drug development. In addition, zinc(II) complexes catalyze aldol and Claisen condensations, which allow for the formation of β-hydroxy ketones and esters. Zinc plays a critical role in facilitating the formation of enolates, which are necessary intermediates in these reactions and are widely utilized in constructing carbon skeletons in organic synthesis.

Another important application of zinc(II) complexes is in asymmetric catalysis. The development of chiral zinc(II) complexes has opened new avenues in asymmetric synthesis, where these catalysts promote reactions that yield enantiomerically pure products, essential in the pharmaceutical industry. For instance, chiral zinc complexes are used in the asymmetric synthesis of amino acids and natural products. Zinc(II) complexes are also gaining attention in environmental applications due to their role in promoting eco-friendly and sustainable catalytic processes. These complexes enable reactions to proceed under mild conditions and with minimal waste production, aligning with the principles of green chemistry. Zinc-based catalysts are used to facilitate the degradation of pollutants and the synthesis of biodegradable polymers, contributing to sustainable development goals.

In addition to their industrial and synthetic applications, zinc(II) complexes are also utilized in biological systems. They can serve as enzyme mimics, providing insights into the catalytic mechanisms of metalloenzymes. By mimicking the active sites of enzymes, these complexes enable researchers to explore the roles of metals in biological transformations and develop synthetic pathways that replicate natural processes. This makes zinc(II) complexes valuable tools in bioinorganic chemistry, particularly in the design of biomimetic catalysts.

Zinc(II) complexes offer several advantages as catalysts. They exhibit high selectivity in catalyzing specific reactions, often leading to the formation of desired products with minimal side reactions, which is particularly important in synthetic organic chemistry. Additionally, many zinc-catalyzed reactions can proceed under mild conditions, such as ambient temperature and atmospheric pressure, making these complexes attractive for industrial applications where reducing energy consumption and operational costs is crucial. Zinc is an abundant and environmentally benign metal, making zinc(II) complexes a sustainable choice for catalysis. Their use aligns with green chemistry principles, promoting eco-friendly practices in chemical synthesis. Moreover, compared to other transition metal catalysts, zinc complexes are often more cost-effective, which makes them appealing for large-scale industrial applications, particularly in the production of pharmaceuticals and fine chemicals.

Despite their numerous advantages, there are challenges associated with the use of zinc(II) complexes in catalysis. One issue is the stability of some zinc complexes, which may be limited under certain reaction conditions, leading to catalyst deactivation. Research into developing more robust complexes or encapsulating them within support materials could improve their stability and longevity. Another challenge is the relatively limited scope of reactions that can be catalyzed by zinc(II) complexes. Expanding their applicability to a broader range of organic transformations will require further exploration and optimization of ligands and reaction conditions. Scaling up laboratory-scale reactions to industrial-scale applications also presents challenges, and research into the scalability of zinc-catalyzed processes is necessary to ensure their viability in large-scale manufacturing. Finally, a deeper mechanistic understanding of how zinc(II) complexes catalyze reactions is essential for designing more effective catalysts. Ongoing studies that employ advanced characterization techniques and computational modeling will be key to providing valuable insights into the catalytic mechanisms of zinc(II) complexes and informing future developments in this field.[72]

4.1.2.b) Sensors

Zinc(II) complexes have become a focal point of interest in sensor development due to their remarkable physicochemical properties, such as stability, selectivity, and the ability to respond reversibly to environmental changes. These features make them highly suited for diverse sensing applications, especially in detecting biological and chemical analytes. The versatility of zinc complexes extends across multiple domains, ranging from environmental monitoring to biomedical diagnostics. As this article explores, the unique attributes of zinc(II) complexes make them invaluable tools in the field of sensor technology, particularly due to their varied detection mechanisms, affordability, and potential for scalability.

Zinc(II) complexes are coordination compounds that form when zinc ions (Zn^{2+}) interact with a wide array of ligands, such as organic molecules, proteins, or even inorganic species. The nature of these ligands plays a significant role in determining the electronic properties and reactivity of the zinc complexes, thus affecting their overall effectiveness in sensing applications. Zinc, being a biologically relevant metal, is already integral to many physiological processes, enhancing the utility of its complexes in biological and medical sensing applications. In this regard, zinc(II) complexes are particularly valuable because their chemical structure can be finely tuned to detect specific substances, making them adaptable to various analytical needs.

One of the most widespread applications of zinc(II) complexes in sensor development is in fluorescence-based sensing. Zinc complexes can exhibit fluorescence that changes in response to particular analytes, either through an increase or decrease in intensity or a shift in the wavelength of emission. When an analyte binds to the zinc complex, it often alters the electronic environment around the zinc ion, leading to these detectable changes. This mechanism is particularly useful for detecting metal ions, anions, or small organic molecules. Similarly, colorimetric sensing utilizes zinc(II) complexes capable of undergoing color changes upon interaction with target analytes. This shift in color can be observed visually or quantified through spectrophotometry, allowing for quick and reliable detection, especially in field applications where sophisticated instrumentation may not be available.

Zinc(II) complexes also find applications in electrochemical sensing, where they can enhance the sensitivity and specificity of sensors. The redox properties of zinc allow these complexes to participate in electron transfer reactions, generating measurable electrical signals upon the binding of an analyte. Such electrochemical sensors are especially valuable in detecting a broad range of substances, including heavy metals and biological markers, making them critical in environmental monitoring and clinical diagnostics. Additionally, zinc complexes can be incorporated into sensors that operate based on changes in electromagnetic properties. For instance, the binding of certain analytes can modify the dielectric constant or conductivity of the zinc complex, leading to a detectable response. This capability further expands the scope of zinc(II) complexes in sensor development.

In biological sensor development, zinc(II) complexes are highly effective in detecting metal ions like copper(II), lead(II), and mercury(II). These sensors are designed with the selective binding of zinc complexes to specific metal ions, triggering measurable changes in fluorescence or color. Such applications are crucial in environmental monitoring, especially in detecting metal ion contamination, which poses significant health risks. Zinc complexes are also utilized in biomarker detection, where they can be tailored to bind specific biomolecules like proteins or nucleic acids. The resulting signal from this binding enables the detection of important disease biomarkers, making zinc(II)-based sensors invaluable tools in early disease diagnosis and monitoring. For example, sensors developed for detecting glucose, cholesterol, or cancer markers have shown promise in improving diagnostic capabilities, potentially enhancing patient outcomes through early intervention.

Environmental sensor technology has also benefited from zinc(II) complexes, particularly in water quality monitoring. These complexes can selectively bind to contaminants like heavy metals, pesticides, and pathogens, providing sensitive detection systems that contribute to public health and environmental protection. Moreover, the use of zinc complexes in air quality sensors has gained attention. These sensors can detect volatile organic compounds (VOCs) and other gaseous pollutants, offering a valuable resource for environmental monitoring and pollution control.

In the food industry, zinc(II) complexes have been employed in the development of sensors for food safety and quality control. These sensors can detect contaminants such as harmful bacteria (e.g., Salmonella and E. coli) or chemical residues in food products. By utilizing the selective binding properties of zinc complexes, rapid and accurate detection of foodborne pathogens can be achieved, ensuring the safety of the food supply chain. Additionally, zinc-based sensors play a key role in assessing the freshness and quality of food by monitoring spoilage indicators or changes in pH and temperature, thus reducing food waste and enhancing consumer safety.

The potential for zinc(II) complexes in wearable sensor technology is another exciting area of development. These complexes can be integrated into wearable devices for continuous health monitoring. For instance, sensors that detect glucose levels in sweat, using zinc complexes, offer a non-invasive method of monitoring blood sugar levels, providing an alternative for diabetes management. This application not only enhances patient comfort but also opens new avenues for personalized healthcare.

The advantages of zinc(II) complexes in sensor technology are numerous. They can be designed to exhibit high selectivity for specific analytes, which minimizes interference from other substances and increases sensitivity, making it possible to detect even trace amounts of target analytes. Their biocompatibility is another significant benefit, particularly in medical applications, as they can function in physiological conditions without causing adverse effects. The diverse detection mechanisms—ranging from fluorescence to electrochemical responses—enable the development of sensors for a wide variety of applications. Furthermore, the abundance and low cost of zinc as a metal make zinc(II) complexes a cost-effective choice for sensor development, particularly in developing regions where affordability is a major consideration.

Despite their advantages, zinc(II) complexes face some challenges in sensor development. One of the primary issues is ensuring the stability of these complexes under various environmental conditions, as instability can lead to deactivation or poor performance of the sensor. Additionally, when used in complex biological or environmental matrices, zinc(II) complexes may be affected by matrix effects or interference from other substances. Addressing these challenges requires ongoing research to optimize sensor designs and improve selectivity. Furthermore, the integration of zinc complexes into advanced technologies like microfluidic devices or lab-on-a-chip systems presents opportunities to enhance sensor capabilities, offering miniaturized and automated sensing platforms for various applications.

In the realm of medical diagnostics, ensuring that sensors based on zinc(II) complexes meet regulatory requirements is another hurdle that needs to be overcome. Medical devices must undergo rigorous testing and validation to ensure their safety and efficacy before they can be commercialized. This process, while challenging, is essential for ensuring that zinc(II)-based sensors are reliable tools for healthcare professionals and patients alike.

In conclusion, zinc(II) complexes hold immense promise in the field of sensor development due to their unique properties, including selectivity, versatility, and cost-effectiveness. Their applications in biological, environmental, and food safety sensors, along with the potential for integration into wearable health devices, make them a powerful tool for future technological advancements. However, challenges such as stability, matrix effects, and regulatory approval must be addressed to fully realize their potential. As research continues, zinc(II) complexes are likely to play an increasingly important role in the development of next-generation sensor technologies, contributing to advancements in public health, environmental protection, and beyond.[73]

4.1.2.c) Agriculture

Zinc is an essential micronutrient crucial for plant growth and development, playing a fundamental role in various physiological processes such as enzyme function, protein synthesis, and chlorophyll production. However, zinc deficiency is prevalent in many agricultural soils, leading to poor crop yield, reduced quality, and diminished overall plant health. This issue has driven increased interest in the application of zinc(II) complexes in fertilizers and pesticides to enhance agricultural productivity and sustainability. The use of zinc(II) complexes addresses zinc deficiencies while supporting broader agricultural goals, improving both plant nutrition and resilience.

Zinc deficiency in crops manifests in several ways, negatively affecting both yield and quality. Deficient plants often show stunted growth due to impaired cell division and elongation, with smaller leaves that are more vulnerable to environmental stress. Interveinal chlorosis is another common symptom, where the tissue between leaf veins turns yellow, impeding photosynthesis and weakening plant vigor. The overall reduction in crop yield caused by zinc deficiency is particularly problematic for staple crops such as wheat, rice, and maize, which are sensitive to zinc shortages and vital for global food security. In addition to diminished yields, zinc deficiency also impacts crop quality, lowering protein content and reducing grain nutritional value. Addressing this deficiency through the use of zinc(II) complexes in agricultural applications is critical for improving both crop yield and quality.

Zinc(II) complexes have emerged as important components in fertilizers, offering numerous advantages over traditional zinc sources. These complexes are often more soluble in soil and plant solutions than conventional zinc salts, ensuring that zinc is more readily available for plant uptake. This enhanced bioavailability increases the nutrient's effectiveness, supporting healthier plant growth. Furthermore, some zinc complexes are formulated for controlled release, providing a steady supply of zinc over time. This minimizes the risk of leaching, which can lead to nutrient loss and environmental contamination, making zinc(II) complexes more efficient and environmentally friendly. Their compatibility with other essential nutrients, such as nitrogen and phosphorus, allows for the creation of balanced fertilizers that address multiple nutrient deficiencies, promoting overall plant health. Research indicates that zinc fertilizers can significantly improve crop growth rates, enhance root development, and increase resistance to diseases and pests. Zinc(II) complexes can be applied in various ways, including soil application, foliar spraying, and seed treatment, with foliar applications offering a rapid response to zinc deficiency.

In addition to their role in plant nutrition, zinc(II) complexes are effective in plant protection, helping to enhance plant resistance to diseases and pests. Zinc(II) complexes have inherent antimicrobial properties that can inhibit the growth of pathogens like bacteria, fungi, and viruses, providing a natural defense against diseases and reducing the need for chemical fungicides and bactericides. Moreover, the application of zinc(II) complexes can trigger systemic acquired resistance (SAR) in plants, a defense mechanism that enhances the plant's ability to fend off pathogens and pests. Zinc also helps plants cope with environmental stressors such as drought, salinity, and heavy metal toxicity, improving root function and nutrient uptake under adverse conditions. These complexes can be integrated into sustainable pest management strategies, reducing reliance on chemical pesticides and supporting ecological balance. By promoting efficient photosynthesis through chlorophyll production, zinc(II) complexes ensure better growth and higher crop yields.

Beyond fertilization and disease control, zinc(II) complexes play a role in comprehensive crop management practices. They are particularly valuable in soil remediation, where they help stabilize and immobilize heavy metals in contaminated agricultural soils, preventing their uptake by crops and ensuring food safety. Precision agriculture techniques, which rely on soil testing and nutrient analysis, can optimize the application of zinc(II) complexes, allowing for targeted interventions that maximize efficiency and minimize waste. Incorporating zinc(II) complexes into crop rotation and diversification strategies also helps maintain soil health, as different crops have varying zinc requirements. These complexes contribute to sustainable agriculture by promoting soil health, reducing the need for chemical inputs, and enhancing crop resilience, ultimately improving the environmental sustainability of farming practices.

Despite their many benefits, the application of zinc(II) complexes in agriculture comes with challenges that must be addressed. The cost of producing and applying these complexes can be higher than traditional fertilizers, requiring careful evaluation of cost-effectiveness by farmers. Excessive application of zinc can lead to accumulation in soils and water bodies, potentially causing toxicity, so careful management and adherence to recommended application rates are essential. The interaction of zinc(II) complexes with soil components, including pH, organic matter, and competing ions, can also affect their availability and effectiveness, making it necessary to understand soil chemistry when applying these products. Education and awareness programs are crucial for helping farmers and agricultural stakeholders understand the benefits of zinc(II) complexes and adopt them effectively.[74]

Looking ahead, the future of zinc(II) complexes in agriculture is promising, with ongoing research exploring several key areas. The development of zinc(II) nanocomplexes offers the potential for improved solubility and bioavailability, allowing for more efficient nutrient delivery to plants. Biologically derived zinc(II) complexes, such as those formed with plant extracts or natural polymers, may offer improved environmental compatibility and reduced toxicity concerns. Innovative formulations that combine zinc(II) complexes with other nutrients or bioactive compounds could create multifunctional fertilizers that address multiple deficiencies while promoting plant health. Integrating zinc(II) complexes with sustainable practices such as cover cropping, organic amendments, and conservation tillage can further enhance soil health and crop productivity. Establishing clear regulatory frameworks for the use of zinc(II) complexes in agriculture will be essential to ensure safety and efficacy while fostering innovation in this field.

In conclusion, zinc(II) complexes offer a range of benefits in agriculture, from improving soil fertility and plant nutrition to protecting crops from diseases and environmental stressors. Their application in fertilizers, plant protection, and overall crop management holds great promise for enhancing agricultural productivity and sustainability. However, addressing challenges related to cost, environmental impact, and education is critical to maximizing the potential of these complexes in modern farming practices. With continued research and innovation, zinc(II) complexes are poised to play an increasingly important role in sustainable agriculture.

4.2. Applications of Mercury(II) Complexes

4.2.1 Biological Applications

Mercury(II) complexes have significant biological applications, particularly in medicinal chemistry and biochemistry. These complexes exhibit antibacterial, antifungal, and anticancer properties, making them valuable in developing new therapeutic agents. Their mechanisms of action often involve interactions with cellular components, such as proteins and nucleic acids, leading to disruption of cellular processes and induction of apoptosis in cancer cells. Additionally, mercury(II) complexes are explored for their potential in targeted drug delivery systems, improving the solubility and bioavailability of poorly soluble drugs. However, their use is limited by mercury's toxicity, necessitating careful consideration in pharmaceutical applications.[75]

4.2.1.a) Antibacterial Activity Evaluation

Hg(II) complexes exhibit remarkable antibacterial activity through their multifaceted mechanisms of action, making them potent agents against a broad spectrum of bacterial strains. The primary mechanism by which these complexes exert their antibacterial effects is through interaction with bacterial cell walls and membranes. The soft acidic nature of Hg(II) allows it to form strong bonds with soft bases, such as sulfur and nitrogen atoms found in bacterial proteins and enzymes. This binding capability leads to several critical effects that undermine bacterial viability.

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, resulting in the leakage of cellular contents and ultimately leading to bacterial cell death. Additionally, Hg(II) complexes can bind to bacterial DNA, causing cross-linking and strand breakage, which interferes with DNA replication and transcription, further contributing to their antibacterial efficacy.

The broad-spectrum activity of Hg(II) complexes is evident in their effectiveness against various bacterial strains. For Gram-positive bacteria, complexes containing Schiff base ligands have demonstrated strong inhibitory effects against *Staphylococcus aureus*.

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

	Zone of Inhibition(mm)		
Compound	**E. coli**	**Pseudomonas aeruginosa**	**Staphylococcus aureus**
$[(\mu\text{-}Cl)_2\{Hg_2L_3Cl_2\}]_n$	12	18	20
$[Hg_2L_3Br_4][(\mu\text{-}Br)_2\{Hg_2L_3Br_2\}]_n$	14	17	22
$[(\mu\text{-}Br)_2\{Hg_2L_3Br_2\}]_n$	13	19	21
$[Hg_2L_3I_4]$	15	18	24
$[Hg_2L_1(SCN)_4]$	13	16	20
$[(-1,3\text{-}SCN)_2\{Hg_2L_1(SCN)_2\}]_n$	14	17	22
$[HgL_2Cl]_2[Hg_2Cl_6]$	12	19	23
$[Hg(L_2)(-I)HgI_3]$	11	18	21
$[(-Cl)_2\{Hg_2L_3Cl_2\}]_n$	12	20	22
$[Hg_2L_4Cl_4]$	13	18	19
Complex (HMBT-Hg)	14	17	23
$[HgCl_2L]$	12	18	20

[Hg((2,6-Cl-ba)$_2$en)Br$_2$]	15	19	24
Reference Drug (Tetracycline)	15	21	25

This effectiveness is particularly noteworthy given the pathogenic nature of *Staphylococcus aureus* and its tendency to develop resistance to many conventional antibiotics. Hg(II) complexes have also demonstrated efficacy against Gram-negative bacteria such as *Pseudomonas aeruginosa* and *Escherichia coli*. Their ability to target both Gram-positive and Gram-negative bacteria highlights their versatility and broad applicability in treating bacterial infections.[76]

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. 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.

4.2.1.b) Anticancer Properties

Mercury(II) complexes have garnered increasing attention due to their potential anticancer properties, showcasing a range of biological activities that include selectively targeting cancer cells and inducing cell death. As research in this area continues, these complexes are emerging as a promising avenue in cancer therapy. Their ability to interact with biological molecules, induce apoptosis, generate reactive oxygen species (ROS), and inhibit cellular proliferation places them at the forefront of new therapeutic approaches. However, significant challenges associated with toxicity, mechanistic understanding, and clinical application must be addressed for these complexes to fulfill their therapeutic potential.

Mercury(II) ions have the capacity to interact with key biological molecules such as proteins, enzymes, and nucleic acids. These interactions can alter protein function and enzyme activity, thereby disrupting critical cellular processes. Mercury, known for binding to sulfhydryl groups in proteins, can induce conformational changes, which may result in the loss of protein function. This phenomenon is particularly relevant in cancer cells, which are characterized by altered protein expression and function. By targeting these specific features of cancer cells, mercury(II) complexes can disrupt essential processes that are required for cell survival and proliferation.

One of the primary mechanisms by which mercury(II) complexes exert their anticancer effects is through the induction of apoptosis, a process of programmed cell death that is essential for eliminating damaged or diseased cells. Apoptosis can be triggered by several stress signals, such as DNA damage, oxidative stress, and dysregulated signaling pathways. Mercury(II) complexes have been shown to activate apoptotic pathways within cancer cells, leading to cell cycle arrest and eventual cell death. This is often mediated through the activation of caspases, which are critical proteins involved in the execution phase of apoptosis. The ability of mercury(II) complexes to selectively induce apoptosis in cancer cells while sparing normal cells is one of their most promising features, as it could offer a more targeted approach to cancer treatment compared to conventional chemotherapy.

Another key mechanism by which mercury(II) complexes demonstrate anticancer activity is through the generation of reactive oxygen species (ROS). ROS are highly reactive molecules that can cause significant damage to cellular components, including lipids, proteins, and DNA. Cancer cells are often characterized by elevated levels of ROS due to their high metabolic activity, but they also rely on enhanced antioxidant systems to neutralize the toxic effects of ROS. By further increasing ROS levels, mercury(II) complexes can overwhelm these defense mechanisms, leading to oxidative stress and cell death. The generation of ROS also has the potential to enhance the effectiveness of other therapeutic agents, suggesting that mercury(II) complexes could serve as valuable adjuvants in combination cancer therapies.

In addition to their ability to induce apoptosis and generate ROS, mercury(II) complexes have shown the capacity to inhibit cellular proliferation in cancer cells. This inhibition may result from interference with essential signaling pathways that regulate cell growth and division. By disrupting these pathways, mercury(II) complexes can effectively slow down or halt tumor growth. This effect on cellular proliferation further enhances the therapeutic potential of these complexes in the treatment of cancer.

Numerous mercury(II) complexes have been studied for their anticancer properties, and several examples stand out for their notable biological activities. Mercury(II) complexes with Schiff base ligands, for instance, have been extensively investigated for their ability to induce apoptosis in human cancer cell lines. Schiff base ligands, which are formed by the condensation of aldehydes and primary amines, are known for their diverse biological activities. Studies have demonstrated that mercury(II) complexes with Schiff base ligands can activate caspases and alter mitochondrial membrane potential, thereby triggering apoptotic cell death in cancer cells such as HeLa (cervical cancer) and MCF-7 (breast cancer) cells.

Mercury(II) complexes with dithiocarbamate ligands have also shown significant promise in cancer therapy. Dithiocarbamates are known for their strong chelating ability and have been studied for various biological applications. Mercury(II) complexes with these ligands have demonstrated the ability to inhibit cancer cell proliferation, induce apoptosis, and increase ROS production. These effects are thought to arise from the disruption of redox balance within cancer cells, as well as the activation of stress response pathways. Given their strong anticancer properties, mercury(II) complexes with dithiocarbamate ligands are being explored as potential candidates for further preclinical and clinical studies.

Additionally, mercury(II) complexes with polyamine derivatives have been shown to exert significant anticancer effects. Polyamines are organic compounds that play key roles in cellular processes such as cell growth and differentiation. By forming complexes with polyamines, mercury(II) can interfere with polyamine metabolism and disrupt cellular growth signals, leading to the inhibition of cancer cell proliferation and the induction of cell death. These complexes represent another promising class of mercury(II)-based compounds with potential applications in cancer therapy.

Mercury(II) complexes incorporating natural products have also been explored for their enhanced anticancer activity. Natural products, such as flavonoids and alkaloids, are known for their therapeutic properties, and when combined with mercury(II), these compounds can exhibit synergistic effects. The resulting mercury(II) complexes may benefit from the bioactivity of the natural products while also leveraging the unique anticancer properties of mercury. These combinations have shown the potential to effectively target cancer cells, further expanding the range of mercury(II) complexes being considered for cancer treatment.

The therapeutic potential of mercury(II) complexes in cancer treatment extends beyond their ability to target cancer cells directly. Their selectivity in inducing apoptosis specifically in cancer cells, while minimizing damage to normal cells, makes them attractive candidates for targeted therapies. Targeted cancer therapies are designed to attack specific molecular targets that are involved in the growth and survival of cancer cells, reducing the side effects associated with traditional chemotherapy. Mercury(II) complexes, with their selective cytotoxicity, could play an important role in developing more precise and less toxic cancer treatments.

Moreover, the ability of mercury(II) complexes to generate ROS and enhance oxidative stress in cancer cells suggests that they could be used in combination with other therapeutic agents. Combination therapies, which involve the use of multiple drugs or treatments, are increasingly being explored as a way to improve treatment outcomes and overcome drug resistance in cancer. By enhancing oxidative stress, mercury(II) complexes could potentiate the effects of other anticancer agents, making them an attractive option for use in combination therapies.

Despite the promising anticancer properties of mercury(II) complexes, several challenges must be addressed before they can be considered for clinical use. One of the most significant concerns is their inherent toxicity. Mercury is known for its toxic effects, which can pose serious risks to human health. Therefore, careful consideration of the therapeutic window—the range of doses at which a drug is effective without being toxic—is critical when designing mercury(II) complexes for cancer therapy. Extensive in vivo studies are needed to evaluate the safety profiles of these compounds, as well as to determine their long-term effects on patients.

Another challenge lies in the incomplete understanding of the mechanisms by which mercury(II) complexes exert their anticancer effects. While many studies have demonstrated the ability of these complexes to induce apoptosis, generate ROS, and inhibit proliferation, further research is needed to elucidate the precise molecular pathways involved. A more comprehensive understanding of these mechanisms will aid in the rational design of mercury(II) complexes with optimized efficacy and reduced toxicity.

Regulatory hurdles also represent a significant barrier to the clinical application of mercury(II) complexes. Given the toxicity concerns associated with mercury, regulatory agencies may be hesitant to approve mercury-based compounds for therapeutic use. Rigorous testing and evaluation will be necessary to demonstrate that the benefits of these complexes outweigh the risks. Additionally, the development of advanced drug delivery systems that can target mercury(II) complexes specifically to cancer cells may help mitigate toxicity concerns and improve the safety profile of these compounds.

In conclusion, mercury(II) complexes hold significant promise as potential anticancer agents. Their ability to interact with biological molecules, induce apoptosis, generate ROS, and inhibit proliferation makes them attractive candidates for cancer therapy. However, the challenges associated with their toxicity, incomplete mechanistic understanding, and regulatory concerns must be addressed to fully realize their therapeutic potential. Ongoing research, particularly in the areas of targeted therapy, combination therapy, and drug delivery systems, will be crucial in advancing mercury(II) complexes from experimental compounds to viable anticancer treatments. With further development and refinement, these complexes could represent a new frontier in cancer therapy, offering more effective and less toxic treatment options for patients.[77]

4.2.1.c) Antimicrobial Agents

Mercury(II) complexes have long been recognized for their significant antimicrobial properties, which have made them valuable in fields such as medicine, agriculture, and industry. As antimicrobial resistance becomes an increasingly urgent global issue, there is growing interest in exploring new antimicrobial agents that can effectively combat a wide range of pathogens. Mercury(II) complexes have emerged as promising candidates in this search due to their ability to interact with microbial cells and inhibit their growth.

Antimicrobial agents are substances that either kill or inhibit the growth of microorganisms, which include bacteria, viruses, fungi, and parasites. Over the past several decades, the rise of antibiotic resistance among pathogens has become a critical challenge in treating infections. This resistance has driven the search for alternative antimicrobial agents, with mercury(II) complexes standing out for their broad-spectrum antimicrobial activity. These complexes have demonstrated efficacy against various types of microorganisms, including bacteria, fungi, and viruses, making them a versatile tool in the fight against microbial infections. Their effectiveness is influenced by several factors, including the chemical structure of the complex, concentration, pH, and the type of microorganism being targeted.

The antimicrobial activity of mercury(II) complexes has been particularly well-documented in the context of bacterial infections. Mercury(II) complexes have been shown to exhibit strong antibacterial activity against both gram-positive and gram-negative bacteria, which are two major groups of bacteria distinguished by the composition of their cell walls. In the case of Escherichia coli, a common pathogenic bacterium responsible for infections such as urinary tract infections and gastroenteritis, mercury(II) complexes have demonstrated bactericidal properties. These complexes can disrupt the bacterial cell wall, leading to cell lysis and ultimately killing the bacterial cells. This mechanism is critical because the integrity of the cell wall is essential for bacterial survival, and its disruption can lead to rapid cell death.

Similarly, mercury(II) complexes have shown effectiveness against Staphylococcus aureus, a gram-positive bacterium that is a frequent cause of skin infections, pneumonia, and other serious conditions. In this context, mercury(II) complexes interfere with the synthesis of essential cellular components, impairing bacterial growth and leading to cell death. This ability to disrupt key bacterial processes highlights the potential of mercury(II) complexes as potent antibacterial agents. Even more significantly, mercury(II) complexes have exhibited potential in treating infections caused by Pseudomonas aeruginosa, a bacterium known for its resistance to many conventional antibiotics. The opportunistic pathogen P. aeruginosa is particularly challenging to treat due to its inherent resistance mechanisms, but mercury(II) complexes have shown promise in inhibiting its growth, offering a potential alternative for managing infections caused by this bacterium.

In addition to their antibacterial properties, mercury(II) complexes have demonstrated antifungal activity, making them effective against a variety of fungal pathogens. Fungal infections are a significant concern, particularly for individuals with weakened immune systems, such as those with HIV/AIDS, cancer patients undergoing chemotherapy, or organ transplant recipients. One of the most well-studied fungal pathogens in this context is Candida albicans, a yeast that commonly causes infections in immunocompromised individuals. Mercury(II) complexes have shown significant antifungal activity against C. albicans, not only inhibiting its growth but also preventing the formation of biofilms. Biofilms are complex communities of microorganisms that adhere to surfaces and are resistant to many antifungal treatments, making them particularly challenging to eradicate. The ability of mercury(II) complexes to target biofilm formation enhances their therapeutic potential in combating difficult-to-treat fungal infections.

Further, mercury(II) complexes have been investigated for their antifungal effects against Aspergillus species, which can cause severe infections in individuals with weakened immune systems. Aspergillus species are molds that can lead to life-threatening conditions such as invasive aspergillosis, a serious infection that affects the lungs and can spread to other organs. The antifungal activity of mercury(II) complexes against these species is attributed to their ability to disrupt the integrity of the fungal cell membrane. Like bacterial cell walls, fungal cell membranes are essential for maintaining cell structure and function. By targeting these membranes, mercury(II) complexes can induce cell death in fungal pathogens, making them effective tools for treating fungal infections.

While the antimicrobial properties of mercury(II) complexes make them valuable in several applications, they are perhaps best known for their use as disinfectants and preservatives. In medical settings, mercury-based compounds have long been used in disinfectants due to their broad-spectrum activity against bacteria, viruses, and fungi. Mercury(II) complexes have also been incorporated into preservatives, where they help prevent the growth of microorganisms in products such as vaccines, topical ointments, and cosmetics. The ability of mercury(II) complexes to inhibit microbial growth in a variety of settings underscores their versatility as antimicrobial agents.

However, despite their promising antimicrobial activity, the use of mercury(II) complexes comes with significant challenges. One of the primary concerns is their toxicity. Mercury is a well-known toxic metal, and its complexes can pose risks to human health and the environment. This toxicity limits the widespread use of mercury(II) complexes, particularly in medical applications where safety is a paramount concern. Efforts to reduce the toxicity of these complexes while preserving their antimicrobial activity are ongoing, with researchers exploring ways to modify the chemical structure of the complexes to enhance their safety profile.

Another challenge is the potential for microbial resistance to mercury(II) complexes. While these complexes have been effective against resistant pathogens like P. aeruginosa, the possibility of microorganisms developing resistance to mercury-based agents cannot be ruled out. This concern highlights the need for continued research into the mechanisms by which mercury(II) complexes exert their antimicrobial effects and how microorganisms may adapt to evade their activity. Understanding these mechanisms will be crucial in developing strategies to mitigate the development of resistance and ensure the long-term effectiveness of mercury(II) complexes as antimicrobial agents.

In conclusion, mercury(II) complexes offer significant promise as antimicrobial agents, with proven activity against a broad spectrum of bacteria, fungi, and viruses. Their ability to disrupt key cellular processes, such as cell wall synthesis and membrane integrity, makes them potent agents in the fight against microbial infections. However, challenges related to toxicity and potential resistance must be carefully managed to fully realize their potential. As research into the antimicrobial activity of mercury(II) complexes continues, these compounds may play an increasingly important role in combating microbial resistance and addressing the growing need for new antimicrobial agents.[78]

4.2.1.d) Antiviral Activity

Research on the antiviral properties of mercury(II) complexes, while limited, has shown promising potential in inhibiting certain viral activities. Preliminary investigations suggest that these complexes may interfere with viral replication, a critical aspect of the viral life cycle. One proposed mechanism is the disruption of viral protein synthesis, which is essential for the assembly of new viral particles. By interfering with the synthesis of viral proteins, mercury(II) complexes can impair the ability of the virus to reproduce within host cells, effectively halting its spread. Additionally, mercury(II) complexes may have the ability to disrupt viral envelopes, which are the outer membranes that protect certain viruses and play a vital role in their infectivity. By damaging these envelopes, the complexes render the virus less capable of infecting host cells, weakening its ability to cause disease. While much of this research is still in the early stages, the initial findings are encouraging, and there is significant interest in further exploring the antiviral potential of mercury(II) complexes. However, the toxicity of mercury remains a significant challenge in translating these findings into clinical applications. The balance between efficacy and safety is crucial, as mercury's known toxicity to human cells complicates its use as a therapeutic agent. Future research will need to focus on modifying the chemical structure of these complexes to enhance their selectivity for viral targets while minimizing harm to human cells. Despite these challenges, the unique antiviral mechanisms of mercury(II) complexes, such as interfering with viral replication and disrupting viral envelopes, present a novel avenue for the development of new antiviral agents, particularly in an era where resistance to conventional antiviral drugs is becoming an increasing concern. Further investigations into their mode of action, spectrum of activity, and potential synergistic effects with other antiviral treatments could open new doors in the treatment of viral infections.

The antimicrobial activity of mercury(II) complexes is primarily attributed to their ability to interact with microbial cells and disrupt essential cellular functions. The following mechanisms have been proposed:

Mercury(II) ions possess a strong affinity for thiol groups (-SH) in proteins, a key feature that plays a significant role in their biological activity, including antimicrobial properties. Thiol groups, found in the side chains of cysteine residues, are essential for maintaining the proper structure and function of many proteins, particularly enzymes that rely on their active sites for catalytic activity. When mercury(II) ions bind to these thiol groups, they form stable mercury-thiol bonds, which result in the disruption of protein structure and lead to significant conformational changes. These changes often cause proteins to lose their functional integrity, inhibiting their biological activity.

The interaction between mercury(II) and thiol groups can be particularly detrimental in the case of enzymes. Enzymes play crucial roles in regulating metabolic pathways, facilitating biochemical reactions that are essential for the survival and growth of microorganisms. The binding of mercury(II) to key cysteine residues in enzymes can result in the blocking of active sites or alterations in the enzyme's overall shape. This disruption can inhibit enzymatic function, leading to a cascade of metabolic failures. For instance, mercury(II) can inactivate enzymes involved in processes such as DNA replication, energy metabolism, and cell wall synthesis, all of which are vital for cellular survival.

In microbial cells, proteins that are particularly rich in thiol groups may be more vulnerable to mercury(II) binding, further amplifying its toxic effects. By inhibiting proteins involved in critical pathways such as ATP production or the synthesis of structural components like the cell wall, mercury(II) can effectively halt microbial growth and lead to cell death. This mechanism of action is one reason why mercury(II) complexes exhibit broad-spectrum antimicrobial activity, as many essential proteins across different types of microorganisms rely on thiol groups for function.

Moreover, mercury's ability to disrupt protein function through thiol binding is not limited to enzymes. Structural proteins, membrane proteins, and transport proteins may also be affected. This can lead to a loss of membrane integrity, impaired transport of nutrients and waste products, and disruption of signal transduction pathways, all of which contribute to the ultimate demise of the microbial cell.

In addition to thiol binding, mercury(II) may interact with other functional groups in proteins, such as amine, carboxyl, and hydroxyl groups, though its preference for thiols is the most pronounced due to the high affinity for sulfur atoms. The strong covalent bond formed between mercury(II) and sulfur disrupts disulfide bridges, which are crucial for maintaining the three-dimensional structure of many proteins. The loss of these disulfide bonds can lead to protein denaturation, causing them to unfold and aggregate, further exacerbating the loss of function.

The disruption of enzymatic and structural proteins by mercury(II) is one of the primary mechanisms behind its antimicrobial action. However, this same mechanism also poses significant challenges in therapeutic applications, as mercury(II) ions can similarly bind to human proteins, leading to toxicity. Therefore, while mercury(II) complexes show promise as antimicrobial agents, their clinical use requires careful balancing of antimicrobial efficacy with potential toxicity to human cells. Research into more selective mercury-based compounds, or strategies to mitigate off-target effects, is ongoing to harness the antimicrobial potential of mercury(II) without causing harm to host organisms.

Mercury(II) complexes are highly effective at disrupting microbial cell membranes, a critical component of their broad-spectrum antimicrobial activity. The cell membrane serves as a protective barrier, maintaining cellular homeostasis by regulating the movement of ions, nutrients, and waste products into and out of the cell. It is also involved in various essential processes such as energy generation, signaling, and maintaining the electrochemical gradients that are necessary for cell survival. When mercury(II) complexes interact with microbial membranes, they can cause significant alterations to the membrane's structure and function, ultimately compromising the cell's viability.

The disruption begins when mercury(II) complexes penetrate the lipid bilayer of the microbial cell membrane. Mercury's high affinity for sulfur and nitrogen-containing functional groups enables it to interact with membrane proteins and phospholipids, which are integral to the membrane's structure and stability. By binding to the thiol groups of membrane proteins or interfering with the lipid components, mercury(II) can alter the membrane's permeability. These interactions weaken the membrane's integrity, causing it to lose its selective permeability, which is crucial for regulating the flow of substances in and out of the cell.

As the membrane's permeability increases, essential ions such as potassium (K+), sodium (Na+), and calcium (Ca2+) begin to leak out of the cell. These ions are vital for various cellular functions, including maintaining osmotic balance, facilitating enzymatic reactions, and driving cellular energy production. The loss of ions disrupts the electrochemical gradients across the membrane, leading to a breakdown in the cell's ability to generate ATP, the primary energy currency of the cell. This energy crisis within the cell further contributes to the loss of viability and initiates cellular death pathways.

Additionally, the leakage of cellular contents, including enzymes, metabolites, and other small molecules, further destabilizes the internal environment of the microorganism. This uncontrolled efflux of materials causes the cell to lose its structural integrity and disrupts metabolic processes that are essential for survival. For example, without proper ion gradients, processes like active transport become inefficient, depriving the cell of necessary nutrients and preventing the removal of toxic metabolic byproducts.

One of the most critical consequences of mercury(II)-induced membrane disruption is the onset of cell lysis. The microbial membrane, now compromised, is unable to maintain the pressure differences between the inside and outside of the cell. This leads to an influx of water into the cell, causing it to swell and eventually rupture. The physical bursting of the cell releases its contents into the surrounding environment, effectively leading to cell death.

The disruption of membrane integrity by mercury(II) complexes is not only limited to bacterial cells but also extends to other types of microorganisms, including fungi and viruses. In fungi, for example, the mercury(II) complexes can interact with the ergosterol in fungal cell membranes, which plays a similar role to cholesterol in animal cells, maintaining membrane fluidity and integrity. The disruption of ergosterol can cause similar membrane destabilization and leakage of cellular contents in fungi, leading to antifungal activity.

In viral pathogens, although they do not have the same type of cell membrane as bacteria and fungi, mercury(II) complexes may disrupt the viral envelope (in enveloped viruses). The viral envelope is critical for viral entry into host cells and protecting viral genetic material. When the envelope is compromised, the virus becomes unable to infect host cells effectively, thereby inhibiting viral replication.

In summary, mercury(II) complexes' ability to disrupt microbial cell membrane integrity is a key factor in their antimicrobial action. By penetrating the membrane and altering its permeability, mercury(II) complexes cause critical ion leakage, destabilize the internal environment, and eventually lead to cell lysis. This mechanism, combined with other mercury(II)-mediated effects, such as protein binding and oxidative stress induction, makes these complexes powerful antimicrobial agents. However, this same disruptive capability can pose toxicity risks to host organisms, underscoring the need for careful consideration in therapeutic applications.

Mercury(II) complexes are known to induce the generation of reactive oxygen species (ROS) within microbial cells, which plays a significant role in their antimicrobial activity. ROS are chemically reactive molecules containing oxygen, such as superoxide anions (O2-), hydrogen peroxide (H2O2), and hydroxyl radicals (OH-). Under normal conditions, microbial cells maintain a delicate balance between the production of ROS and their neutralization by antioxidant defense systems, which include enzymes like superoxide dismutase (SOD), catalase, and glutathione peroxidase. However, when ROS production becomes excessive—such as in the presence of mercury(II) complexes—the balance is disrupted, resulting in oxidative stress.

The generation of ROS by mercury(II) complexes is often initiated through interactions with cellular components, particularly metal-containing enzymes and redox-active molecules. For instance, mercury(II) can interfere with the electron transport chain in the microbial cell's mitochondria or analogous structures, leading to leakage of electrons that react with molecular oxygen to form superoxide radicals. Additionally, mercury's affinity for thiol groups in proteins can impair the function of antioxidant enzymes, weakening the cell's ability to detoxify ROS. This sets the stage for a toxic buildup of these reactive species.

Once inside the microbial cell, ROS cause significant oxidative damage to key biomolecules, leading to widespread cellular dysfunction. Lipids, which are a major component of cellular membranes, are particularly vulnerable to ROS. The interaction between ROS and membrane lipids leads to lipid peroxidation, a process where free radicals steal electrons from the lipids in cell membranes, causing structural damage and loss of membrane integrity. This oxidative damage makes the membrane more permeable, contributing to cell leakage and compromising its ability to maintain homeostasis, which can eventually lead to cell death.

Proteins are another critical target of ROS within microbial cells. ROS can oxidize amino acid side chains, particularly those containing sulfur, such as cysteine and methionine. This oxidative modification of proteins can result in the loss of their three-dimensional structure, disrupting their function. Since proteins are responsible for carrying out virtually all cellular processes—including enzymatic reactions, signal transduction, and structural support—their inactivation by ROS can have catastrophic effects on the cell's survival. For example, the oxidative damage to enzymes involved in energy production or DNA replication can halt microbial growth and division, contributing to the overall antimicrobial effect of mercury(II) complexes.

Furthermore, ROS can directly attack the microbial cell's DNA, causing oxidative damage to nucleotides. This damage can manifest as strand breaks, base modifications, or cross-linking, which can interfere with DNA replication and transcription. The accumulation of such DNA damage can lead to mutations or trigger cell cycle arrest, preventing the microorganism from proliferating. In extreme cases, extensive DNA damage can activate programmed cell death pathways, further contributing to the microbial cell's demise.

The oxidative stress induced by ROS also overwhelms the microbial cell's natural defense mechanisms. Microorganisms typically possess antioxidant enzymes such as superoxide dismutase (SOD), which converts superoxide radicals into less harmful molecules, and catalase, which breaks down hydrogen peroxide into water and oxygen. Mercury(II) complexes can impair the function of these enzymes by binding to their active sites, particularly the thiol groups, reducing their ability to neutralize ROS. As a result, the cell's antioxidant defense system becomes ineffective, leaving it more vulnerable to oxidative damage.[79]

In addition to enzymes, non-enzymatic antioxidants like glutathione, a tripeptide containing a reactive thiol group, also play a crucial role in detoxifying ROS. Mercury(II) can bind to glutathione, depleting its levels and further diminishing the cell's ability to cope with oxidative stress. The depletion of glutathione and other antioxidants exacerbates the oxidative damage, leading to a self-reinforcing cycle where ROS levels continue to rise, causing more damage and further reducing the cell's defenses.

Ultimately, the oxidative stress caused by ROS generation in the presence of mercury(II) complexes leads to widespread cellular dysfunction and eventual cell death. The combined effects of lipid peroxidation, protein oxidation, and DNA damage create a hostile intracellular environment that microorganisms cannot survive. This makes mercury(II) complexes potent antimicrobial agents, as their ability to induce ROS can overwhelm a wide range of pathogens, including bacteria, fungi, and viruses.

However, while the ROS generation is beneficial for the antimicrobial activity of mercury(II) complexes, it also poses significant challenges for their use in therapeutic settings. The same oxidative stress that is toxic to microbial cells can also harm host tissues, leading to side effects such as inflammation and cytotoxicity. Therefore, the use of mercury(II) complexes must be carefully controlled, and research is ongoing to develop strategies that minimize collateral damage to healthy cells while maximizing the antimicrobial benefits. This could include the design of mercury(II) complexes that specifically target microbial cells or the use of delivery systems that limit the exposure of host tissues to the complexes.

In summary, mercury(II) complexes' ability to generate reactive oxygen species within microbial cells is a critical mechanism of their antimicrobial action. By inducing oxidative stress, these complexes cause significant damage to lipids, proteins, and DNA, overwhelming the microbial cell's defense systems and leading to cell death. While this makes them highly effective in combating infections, their potential toxicity to host tissues remains a challenge that must be addressed through further research and development

Some studies suggest that mercury(II) complexes can interact with microbial DNA, disrupting replication and transcription processes. This interference can hinder the ability of microorganisms to grow and reproduce, contributing to their antimicrobial effects.[80]

4.2.1.e) Applications of Mercury(II) Complexes as Disinfectants

Mercury(II) complexes are widely recognized for their potent antimicrobial properties, making them effective disinfectants in various environments, including healthcare settings, laboratories, and industries. Their ability to combat a broad spectrum of microorganisms, including bacteria, fungi, and viruses, enhances their utility in maintaining hygiene and preventing the spread of infections. In healthcare facilities, for instance, mercury(II) complexes are used to disinfect surfaces and medical instruments, reducing the risk of hospital-acquired infections. Their effectiveness against antibiotic-resistant strains adds to their importance in infection control strategies.

In laboratory settings, these complexes help in decontaminating workspaces, ensuring safe handling of microbial cultures and preventing cross-contamination. Moreover, their use in industrial applications, such as wastewater treatment, aids in controlling microbial growth in processes where maintaining a sterile environment is crucial. Despite concerns regarding the toxicity of mercury, careful formulation and application of mercury(II) complexes can maximize their antimicrobial benefits while minimizing risks. Thus, their continued use as disinfectants is essential for promoting public health and safety in various sectors, particularly in an era of increasing microbial resistance.

In the medical field, mercury(II) complexes are used as disinfectants for sterilizing surgical instruments and medical equipment due to their potent antimicrobial properties. Their ability to effectively kill bacteria and fungi makes them highly suitable for maintaining hygiene in healthcare settings. By disinfecting surfaces and instruments, these complexes help reduce the risk of hospital-acquired infections, ensuring a safer environment for both patients and healthcare professionals. Despite their toxicity concerns, careful application allows their use in sterilization, contributing to infection control in medical facilities.

Mercury(II) complexes have been used as disinfectants in agriculture to control fungal and bacterial diseases affecting crops. They can be applied to seeds and soil to prevent infections that can compromise crop yield and quality. However, their use in agriculture raises concerns about environmental toxicity and bioaccumulation.

In industrial settings, mercury(II) complexes are utilized in the formulation of disinfectants and sanitizers for food processing, water treatment, and surface disinfection. Their broad-spectrum antimicrobial activity effectively reduces microbial contamination, ensuring the safety and cleanliness of these environments. In food processing, these complexes help prevent spoilage and contamination, while in water treatment, they control microbial growth. Additionally, their use in surface disinfection maintains hygiene standards in industrial facilities. Despite safety concerns, controlled applications of mercury(II) complexes provide a valuable tool for maintaining microbial control in critical industrial processes.

Mercury(II) complexes are also being explored for their potential as preservatives in various products due to their ability to inhibit microbial growth. By preventing the proliferation of bacteria, fungi, and other microorganisms, these complexes can significantly extend the shelf life of products, particularly in the cosmetic, pharmaceutical, and food industries. Their antimicrobial properties help reduce spoilage and contamination, ensuring product stability over time. Although their use as preservatives is promising, careful consideration of safety and toxicity is essential in developing mercury(II) complexes for widespread application in consumer products.

Mercury(II) complexes have been investigated as preservatives in pharmaceutical formulations, particularly in parenteral preparations, where maintaining sterility is critical. Their potent antimicrobial properties help prevent contamination by bacteria and fungi, ensuring the safety and efficacy of these sterile products during storage and administration. By inhibiting microbial growth, mercury(II) complexes reduce the risk of infections that could arise from contaminated injections or intravenous solutions. However, due to concerns about mercury toxicity, their use is carefully regulated, and alternative preservatives are often considered in modern pharmaceutical practices.

In the cosmetic industry, mercury(II) complexes are sometimes used as preservatives in products such as creams, lotions, and other personal care items. Their antimicrobial properties help prevent the growth of harmful bacteria and fungi, ensuring product safety and extending shelf life. By inhibiting microbial contamination, these complexes maintain the integrity and effectiveness of cosmetic formulations. However, due to concerns about mercury toxicity and its potential health risks, the use of mercury-based preservatives is highly regulated, and safer alternatives are increasingly being sought in cosmetic production.

The food industry has explored the use of mercury(II) complexes for their preservative properties, as they can effectively inhibit microbial growth and extend the shelf life of various food products. However, due to the potential toxicity of mercury, the use of such preservatives in food is subject to stringent regulatory scrutiny. Concerns about mercury's health risks, including its accumulation in the body, have led to strict limitations on its application. Safer and more sustainable alternatives are preferred in modern food preservation to ensure consumer safety while maintaining product quality..

Despite the promising antimicrobial properties of mercury(II) complexes, several challenges must be addressed. Toxicity and safety concerns are paramount, as exposure to mercury can lead to severe health issues, including neurotoxicity and organ damage, necessitating careful management of these compounds. Additionally, the environmental impact is significant, as mercury can accumulate in ecosystems and pose risks to wildlife and human health, prompting regulatory bodies to impose strict limits on its use. Lastly, the potential development of resistance among microorganisms presents a risk, as continued exposure to mercury(II) complexes may select for resistant strains, ultimately diminishing their efficacy.

Future Prospects: Despite the challenges surrounding mercury(II) complexes, research on their use as antimicrobial agents continues to advance. One promising direction is the development of safer alternatives that maintain or improve upon the antimicrobial properties of mercury(II) complexes. Researchers are exploring novel ligands and complexation strategies to enhance the efficacy and safety profiles of these compounds. Additionally, combining mercury(II) complexes with other antimicrobial agents may enhance their effectiveness and reduce the likelihood of resistance development, with potential synergistic effects leading to improved therapeutic outcomes across various applications. Innovative drug delivery systems are also being investigated to enhance the targeted delivery of mercury(II) complexes, minimizing systemic exposure and toxicity while maximizing antimicrobial efficacy. Furthermore, as research progresses, new applications for mercury(II) complexes may emerge in fields such as nanotechnology, materials science, and biotechnology, harnessing their unique properties to provide innovative solutions for combating microbial threats.[81]

4.2.1.f) Binding Studies

Mercury complexes have garnered considerable attention in biological research due to their unique interactions with biomolecules, particularly proteins. Understanding these interactions is crucial for elucidating the mechanisms of mercury toxicity and assessing the effects of heavy metals on cellular functions. Mercury is a heavy metal known for its toxicity, arising from exposure to various forms such as elemental mercury (Hg^0), inorganic mercury (Hg^{2+}), and organic mercury compounds like methylmercury. In biological systems, mercury often forms complexes with biomolecules, which significantly influence their structure and function. Investigating these interactions is essential for understanding mercury's biological effects and its potential therapeutic applications. Binding studies are particularly important for determining how mercury complexes interact with biological macromolecules, including proteins, nucleic acids, and lipids. These interactions can modify the function of biomolecules, leading to various cellular responses such as toxicity, apoptosis, and oxidative stress. Understanding these mechanisms provides insights into several critical areas: toxicological pathways, where unraveling how mercury binds to proteins helps elucidate the routes through which mercury induces toxicity; protein functionality, as understanding how mercury complexes affect protein conformation and function reveals their role in disrupting normal cellular processes;

and therapeutic potential, as studying mercury complexes can yield information relevant to drug design, especially in targeting specific proteins associated with diseases.

Various experimental techniques are employed to study the binding of mercury complexes to proteins, each offering different insights into these interactions. Spectroscopic techniques like UV-Vis spectroscopy are frequently utilized to investigate interactions between mercury complexes and proteins. Changes in the UV-Vis absorption spectrum can indicate the formation of protein-ligand complexes, providing valuable data about binding constants and stoichiometry. Fluorescence spectroscopy is another method employed to examine binding dynamics, where fluorescence quenching experiments reveal quantitative data on binding affinity and dynamics by measuring reductions in fluorescence intensity of fluorescently labeled proteins. Nuclear Magnetic Resonance (NMR) spectroscopy allows researchers to study protein-ligand interactions at the atomic level, as changes in chemical shifts and signal intensities provide insights into binding sites and conformational changes within proteins upon binding to mercury complexes. Additionally, infrared (IR) spectroscopy assesses interactions between mercury complexes and functional groups in proteins, with changes in characteristic absorption bands indicating specific interactions and alterations in protein structure. Chromatographic techniques such as Size-Exclusion Chromatography (SEC) are used to separate protein-ligand complexes based on size, enabling researchers to infer the formation and molecular weights of complexes through analysis of elution profiles. High-Performance Liquid Chromatography (HPLC) is also employed to evaluate binding affinities and kinetics by monitoring the retention times of unbound and bound species. Moreover, mass spectrometry has become increasingly important in binding studies, allowing researchers to characterize protein-ligand interactions by analyzing mass-to-charge ratios of complexes, thus identifying binding sites and quantifying binding stoichiometry. Techniques like matrix-assisted laser desorption/ionization (MALDI) and electrospray ionization (ESI) are commonly used for this purpose. Surface Plasmon Resonance (SPR) serves as a label-free technique, enabling real-time monitoring of protein-ligand interactions by measuring changes in the refractive index near a sensor surface, providing crucial information on binding kinetics, affinity, and concentration of mercury complexes. Lastly, Isothermal Titration Calorimetry (ITC) measures the heat changes during binding events, allowing researchers to glean insights into the thermodynamics of the interactions, including binding affinities, enthalpic and entropic contributions, and stoichiometry.

The mechanisms by which mercury complexes bind to proteins are influenced by several factors, including the complex's chemical structure, the availability of reactive sites on the protein, and the overall environment. Mercury can form coordination bonds with various functional groups in proteins, particularly thiol (-SH) groups in cysteine residues. Such interactions can lead to the formation of stable mercury-thiol complexes that significantly alter protein structure and function. The coordination is influenced by the geometry and sterics of the mercury complex, resulting in varied binding affinities. Additionally, electrostatic interactions between charged regions of mercury complexes and the protein surface contribute to binding affinity; for instance, positively charged mercury complexes may favorably interact with negatively charged protein regions, enhancing their binding. Hydrophobic interactions between nonpolar regions of mercury complexes and hydrophobic patches on proteins can further stabilize the protein-ligand complex and influence conformational changes within the protein.

The biological implications of mercury binding to proteins are significant, particularly concerning toxicity and cellular functions. One primary mechanism of toxicity is enzyme inhibition, where mercury binding to active sites can hinder enzymatic activity, disrupting vital metabolic pathways. For example, mercury can inhibit enzymes involved in energy production and antioxidant defense, leading to oxidative stress and cellular damage. Moreover, the binding of mercury can induce conformational changes in proteins, resulting in misfolding and aggregation. Misfolded proteins can lose functionality and contribute to cellular dysfunction, which can be particularly detrimental. The interaction of mercury with proteins involved in apoptosis can also trigger programmed cell death, a mechanism of interest in cancer research, where mercury complexes are being explored for their potential to induce apoptosis in cancer cells. Additionally, the binding of mercury complexes to signaling proteins can disrupt cellular communication and regulatory pathways, affecting processes such as cell proliferation, differentiation, and apoptosis. Disruption of ion homeostasis is another consequence of mercury binding; mercury complexes can interfere with ion channels and transporters, leading to dysregulation of ion balance, which in turn affects various cellular functions, including neurotransmission and muscle contraction. Furthermore, mercury binding can result in the generation of reactive oxygen species (ROS), causing oxidative damage to proteins, lipids, and DNA, thereby contributing to various pathological conditions such as neurodegenerative diseases and cancer. Understanding these binding interactions and their subsequent biological effects is crucial for developing strategies to mitigate mercury toxicity and explore the potential therapeutic applications of mercury complexes in medicine

Binding studies of mercury complexes hold significant implications across various research fields, providing valuable insights into toxicology, drug design, environmental sciences, and biochemical research. In the field of toxicology, understanding the binding interactions of mercury complexes is essential for elucidating their toxicological mechanisms. By identifying specific proteins that are targeted by mercury, researchers can determine the consequences of these interactions on cellular health. This knowledge helps in revealing the pathways through which mercury induces toxicity, ultimately aiding in the development of strategies to mitigate its harmful effects.

In drug design, mercury complexes are being explored for their potential therapeutic applications, particularly in cancer treatment. By studying the binding interactions between these complexes and proteins associated with cancer progression, researchers can design more effective drug candidates. This could lead to innovative therapeutic approaches that leverage the unique properties of mercury complexes to target cancer cells more selectively, enhancing treatment efficacy while reducing side effects.

Research in environmental sciences also benefits from studies on mercury binding to biomolecules, as it is crucial for assessing the impact of environmental mercury contamination on ecosystems. Understanding how mercury interacts with microbial and plant proteins provides insights into its bioavailability and toxicity in the environment. This knowledge is vital for developing strategies to address mercury pollution and protect ecological systems.

In the realm of biochemical research, binding studies contribute to a deeper understanding of protein structure-function relationships. Investigating how mercury complexes affect protein conformation and activity allows researchers to gain insights into fundamental biochemical processes. These studies can reveal how alterations in protein structure influence cellular functions, thereby enhancing our comprehension of various biochemical pathways.

Despite the valuable insights gained from binding studies of mercury complexes, several challenges remain that researchers must address. One significant challenge is the complexity of biological systems, which presents difficulties in studying mercury binding. Proteins exist in dynamic environments, and their interactions with mercury can be influenced by other cellular components. This complexity complicates the interpretation of binding studies, making it challenging to draw definitive conclusions about the effects of mercury on cellular functions.

Another key challenge is the need for specificity in developing mercury complexes that target particular proteins without affecting others. Achieving this specificity is essential for minimizing toxicity while maximizing therapeutic potential. Researchers must focus on designing complexes that can selectively interact with specific targets, thereby reducing unintended side effects and improving the overall safety profile of these compounds.

Additionally, despite significant advancements in this field, there remain gaps in our understanding of the long-term effects of mercury binding on cellular functions. More comprehensive studies are necessary to elucidate the broader implications of these interactions and to establish a clearer picture of how mercury impacts biological systems over extended periods. This knowledge is critical for both understanding mercury toxicity and exploring its potential therapeutic applications.

Finally, the use of mercury complexes in research and their potential therapeutic applications raises regulatory considerations that must be addressed. Ensuring the safety of mercury-based compounds requires careful consideration of their toxicity and environmental impact. Regulatory bodies must evaluate the risks associated with these compounds and establish guidelines to ensure their safe use in both laboratory and clinical settings. As research continues to evolve, addressing these challenges will be essential for maximizing the benefits of mercury complexes while minimizing their risks.[82]

4.2.2. General Applications OF Mercury(II) complexes

4.2.2.a) Electrochemistry

Mercury(II) complexes have garnered extensive interest in the field of electrochemistry due to their unique properties, which include high electroactivity, the ability to form stable complexes, and sensitivity to various analytes. This article delves into the general applications of mercury(II) complexes in electrochemical sensors, highlighting their mechanisms, the types of sensors developed, advantages and limitations, as well as future prospects.

Electrochemical sensors are analytical devices that convert chemical information into electrical signals, and they have found widespread applications across various fields, including environmental monitoring, food safety, clinical diagnostics, and biomedical research. Their popularity stems from high sensitivity, specificity, and rapid response times. The fundamental principle behind these sensors involves measuring changes in current, voltage, or charge that occur during chemical reactions at an electrode surface. There are three primary types of electrochemical sensors: potentiometric sensors, which measure potential differences between two electrodes without drawing significant current and are commonly used for ion detection; amperometric sensors, which gauge the current produced by redox reactions at an electrode and are widely employed to detect a variety of analytes such as gases, ions, and biomolecules; and impedimetric sensors, which assess the impedance of an electrochemical system, providing information on charge transfer processes occurring at the electrode interface.

Mercury(II) complexes play a crucial role in the advancement of electrochemical sensors due to their unique redox properties and capability to form stable complexes with a variety of analytes. These versatile complexes can function both as the sensing element and as catalysts in electrochemical reactions, enhancing the overall performance of the sensors. One of the notable properties of mercury(II) complexes is their electroactivity. Mercury(II) ions exhibit distinctive electrochemical behavior that allows participation in various redox reactions, making them suitable candidates for sensor applications. Furthermore, mercury(II) can form stable complexes with different ligands, which significantly enhances selectivity and sensitivity toward specific analytes. This complexation leads to considerable changes in the electrochemical response, facilitating the detection of even trace amounts of substances. The electrochemical behavior of mercury complexes also enables the detection of analytes at very low concentrations, making them ideal for trace analysis, while their wide potential window allows for the detection of a broad spectrum of analytes.

The electrochemical detection mechanisms utilizing mercury(II) complexes often involve redox reactions. For instance, when a mercury(II) complex undergoes reduction at the electrode surface, it can yield elemental mercury, which may subsequently interact with the target analyte, thereby amplifying the electrochemical signal. The overall reaction can be summarized as follows $Hg^{2+}+2e^{-}\leftrightarrow Hg$. This reduction process can be coupled with the oxidation of the target analyte, leading to current generation that can be precisely measured. Additionally, the binding of an analyte to the mercury complex can modify the electron density surrounding the mercury center, which in turn influences its electrochemical properties. The formation of a stable complex with the analyte often results in changes to the redox potential of the mercury complex, and these changes can be monitored electrochemically, providing valuable information about the analyte's presence and concentration. Moreover, mercury(II) complexes possess catalytic properties that can enhance the electrochemical reactions associated with the target analytes. This catalytic activity can significantly boost the sensitivity and specificity of the electrochemical sensors, making them more effective for various applications. Overall, the unique properties and versatile applications of mercury(II) complexes in electrochemistry position them as critical components in the development of advanced electrochemical sensors. Their ability to participate in redox reactions, form stable complexes with analytes, and catalyze electrochemical reactions highlights their importance in analytical chemistry, paving the way for innovative solutions to detect and quantify a wide range of substances in diverse fields. As research in this area progresses, the potential for new applications and improved sensor designs continues to expand, making mercury(II) complexes a focal point in the pursuit of enhanced electrochemical sensing technologies.

Types of Electrochemical Sensors Utilizing Mercury(II) Complexes

Mercury-Based Amperometric Sensors: Amperometric sensors that utilize mercury(II) complexes are extensively used for detecting a variety of analytes, including heavy metals, organic compounds, and biomolecules. These sensors usually feature a mercury-modified electrode, where mercury(II) complexes are immobilized on the electrode surface. The presence of these complexes enhances the electrochemical reactions involved in the detection process, allowing for sensitive and selective measurements. When an analyte interacts with the mercury(II) complex, it can induce redox reactions, leading to measurable changes in current. This property enables the detection of low concentrations of analytes, making these sensors valuable in environmental monitoring and biomedical applications.

Heavy Metal Detection: Mercury(II) complexes are widely employed in the detection of heavy metals such as lead (Pb), cadmium (Cd), and copper (Cu) in environmental samples. These complexes interact specifically with the target metals, leading to the formation of stable complexes that produce a measurable current response in amperometric sensors. The sensitivity of mercury(II) complexes allows for the accurate quantification of these metals at low concentrations, making them essential for environmental monitoring and assessment. By leveraging the unique electrochemical properties of mercury complexes, researchers can effectively track pollution levels and ensure compliance with environmental regulations, thereby safeguarding public health and ecosystems.

Biomolecule Detection: Amperometric sensors utilizing mercury complexes have been successfully developed for the detection of biomolecules such as glucose, DNA, and proteins. In these sensors, mercury complexes act as mediators, facilitating electron transfer during redox reactions. When a target biomolecule interacts with the mercury complex, it results in a measurable change in current, indicating the presence and concentration of the analyte. This high sensitivity and specificity make mercury-based amperometric sensors valuable tools in biomedical diagnostics, allowing for real-time monitoring of biomolecular interactions. Their ability to detect low concentrations of biomolecules enhances their applicability in clinical and research settings.

Potentiometric Sensors: Potentiometric sensors that utilize mercury(II) complexes are widely employed for the selective detection of ions in various applications. These sensors typically consist of ion-selective electrodes (ISEs) that are modified with mercury complexes, which enhance their sensitivity and selectivity toward specific ions. The presence of target ions leads to a change in the electrode potential, which can be measured to provide quantitative information about ion concentration. This approach is particularly effective for detecting heavy metal ions and other environmental contaminants, making potentiometric sensors based on mercury complexes valuable tools for environmental monitoring and analysis in laboratory settings.

Ion Detection: Mercury(II) complexes are effectively employed in the construction of ion-selective electrodes (ISEs) for detecting a variety of ions, including fluoride (F^-), chloride (Cl^-), and sulfate (SO_4^{2-}). These ISEs capitalize on the unique properties of mercury complexes, which enhance the sensitivity and selectivity toward target ions. The electrochemical response generated by the interaction between the mercury complex and the target ion enables accurate measurement of ion concentrations. This specificity is crucial for applications in environmental monitoring, water quality assessment, and various analytical chemistry fields, ensuring reliable detection of harmful ions in complex samples.

pH Measurement: Mercury complexes can be effectively utilized in potentiometric pH sensors, where their interaction with protons plays a crucial role in detecting pH levels. When protons bind to the mercury complex, they induce changes in the complex's electrochemical properties, leading to a measurable potential shift. This potential change is directly related to the concentration of hydrogen ions in the solution, allowing for accurate pH measurement. The sensitivity and responsiveness of mercury complexes make them valuable components in the design of pH sensors, enabling reliable monitoring in various applications, including environmental analysis, biochemical research, and industrial processes

Impedimetric Sensors: Impedimetric sensors that utilize mercury(II) complexes offer valuable insights into charge transfer processes at the electrode interface. By measuring changes in impedance, these sensors can effectively detect and quantify analyte concentrations. The incorporation of mercury complexes enhances the sensitivity and selectivity of the sensors, enabling them to discern subtle variations in electrochemical behavior associated with different analytes. This makes impedimetric sensors particularly useful for studying complex systems, including biological samples and environmental matrices. The ability to correlate impedance changes with analyte concentration provides a powerful analytical tool for monitoring various chemical and biological processes in real time.

Impedimetric sensors that incorporate mercury(II) complexes have significant applications in both clinical diagnostics and environmental monitoring. In clinical diagnostics, these sensors excel in biomarker detection, where they provide a sensitive and efficient means of identifying specific biomarkers associated with various diseases. When a biomarker binds to the mercury complex, it alters the charge transfer resistance at the electrode interface. This change can be quantitatively measured, allowing for precise determination of the biomarker's concentration. This capability is crucial for early disease detection and monitoring treatment efficacy.[83]

In the realm of environmental monitoring, impedimetric sensors equipped with mercury complexes can effectively track contaminants in diverse environmental samples, including water, soil, and air. By measuring the impedance changes that occur when specific analytes bind to the mercury complex, these sensors can provide real-time data on the presence and concentration of harmful substances. This application is particularly valuable in assessing pollution levels and ensuring compliance with environmental regulations. The ability to detect low concentrations of contaminants makes these sensors vital tools for protecting public health and the environment. Through their versatile applications, impedimetric sensors utilizing mercury complexes are poised to play a pivotal role in advancing both medical diagnostics and environmental safety.

The use of mercury(II) complexes in electrochemical sensors offers several advantages, including high sensitivity, selectivity, rapid response, and versatility. These complexes enable the detection of analytes at trace concentrations, making them ideal for trace analysis. The ability of mercury to form stable complexes with specific analytes enhances sensor selectivity, allowing for precise detection in complex matrices. Additionally, the rapid response time of mercury-based sensors makes them suitable for real-time monitoring in various fields. Moreover, the flexibility in modifying mercury(II) complexes offers versatility in sensor design, catering to diverse applications.

However, several challenges accompany the use of mercury(II) complexes in electrochemical sensors. Mercury's toxicity poses significant environmental and health risks, requiring strict regulatory controls for handling and disposal. The stability of some mercury complexes can also be compromised under certain conditions, affecting the reliability of the sensor's response. Interference from other ions or compounds present in sample matrices can further compromise the sensor's accuracy and selectivity. Increasing regulatory restrictions on mercury use may also hinder the commercialization and development of mercury-based sensors.

Looking forward, future research will likely focus on overcoming these challenges while maximizing the unique properties of mercury(II) complexes. Eco-friendly alternatives to mercury, such as non-toxic metal complexes or organic compounds, are being explored to reduce environmental impact. Additionally, integrating nanomaterials like graphene and carbon nanotubes into mercury-based sensors can enhance performance by improving conductivity, stability, and sensitivity. Miniaturization through advanced microfabrication techniques will lead to portable, real-time monitoring devices, beneficial in environmental and clinical applications. Hybrid sensors, combining electrochemical and optical detection, may further enhance the functionality and range of applications for mercury(II) complexes. Finally, an increased focus on the interactions between mercury complexes and biomolecules may open new therapeutic applications and insights into environmental toxicity, paving the way for novel sensor technologies [84]

4.2.2.b) Catalysis

Mercury(II) complexes have demonstrated significant potential in catalysis, especially in organic transformations like oxidation and cross-coupling reactions. Despite the known toxicity of mercury compounds, their unique reactivity continues to make them valuable in catalytic applications where other catalysts might face limitations. Catalysis is a vital aspect of modern chemical synthesis, as it enhances reaction efficiency by lowering activation energies and improving selectivity. Mercury(II) complexes, particularly as homogeneous catalysts, are soluble in organic solvents and form stable coordination complexes, facilitating various transformations. Their electron configuration allows them to act as Lewis acids and participate in redox chemistry, making them well-suited for catalyzing oxidation reactions.

The catalytic activity of mercury(II) complexes is largely due to their ability to form stable bonds with organic substrates, activating them for further reactions. For instance, they can coordinate with functional groups, rendering these groups more reactive toward nucleophiles or electrophiles. As Lewis acids, mercury(II) complexes accept electron pairs, making them ideal for reactions that involve the activation of electrophilic centers like carbonyl compounds or alkenes. This ability to stabilize intermediates reduces the energy barrier of reactions, accelerating their rates. In addition, mercury(II) complexes can undergo redox transformations, allowing them to act as electron acceptors in oxidation reactions and facilitating catalytic cycles that require electron transfer.

Furthermore, mercury(II) complexes can activate bonds like C-H, C-C, and C-X, a crucial feature in cross-coupling reactions. By coordinating with the substrate, these complexes reduce the bond dissociation energy, making it easier to cleave and form new bonds. This bond activation ability is one of the reasons mercury(II) is effective in facilitating transformations that require the activation of typically inert bonds. Despite concerns about toxicity, mercury(II) complexes continue to be valuable in catalysis due to their versatility and ability to perform challenging organic transformations

Types of Reactions Catalyzed by Mercury(II) Complexes

Oxidation Reactions: Mercury(II) complexes have been extensively utilized in oxidation reactions, playing a crucial role in converting organic substrates into more oxidized forms. These reactions are fundamental in the production of fine chemicals, pharmaceuticals, and materials, where the ability of mercury(II) to activate substrates and facilitate electron transfer to an oxidizing agent is highly valuable. For example, in alcohol oxidation, mercury(II) complexes can catalyze the transformation of primary alcohols into aldehydes and secondary alcohols into ketones. This process typically involves the coordination of mercury(II) to the hydroxyl group, which enhances electron transfer to the oxidant, making this method useful in synthesizing fine chemicals and pharmaceutical intermediates.

Similarly, mercury(II) complexes are effective in the oxidation of alkenes, converting them into epoxides or diols. These oxidation reactions are important in organic synthesis and are often employed in the creation of intermediates crucial for drug development. The unique reactivity of mercury(II) in these oxidation processes underlines its continued relevance in industrial and pharmaceutical applications, despite concerns about its toxicity.

Cross-Coupling Reactions: Cross-coupling reactions are essential in organic synthesis for forming new carbon-carbon or carbon-heteroatom bonds, enabling the creation of complex organic structures. Mercury(II) complexes have demonstrated significant potential as catalysts in these reactions, particularly for substrates that are challenging to couple with traditional transition metal catalysts. In carbon-carbon coupling, mercury(II) complexes facilitate the formation of C-C bonds by activating one of the coupling partners and promoting electron transfer between the reactants. This process is vital in synthesizing complex organic molecules, including pharmaceuticals and agrochemicals.

In carbon-heteroatom coupling, mercury(II) complexes similarly promote the coupling of carbon atoms with heteroatoms like nitrogen, oxygen, or sulfur, resulting in the formation of C-N, C-O, or C-S bonds. These reactions are especially useful in synthesizing heterocyclic compounds, which are prevalent in biologically active molecules, making them important in pharmaceutical and chemical industries. Mercury's ability to activate challenging substrates positions it as a valuable catalyst in these critical synthetic transformations.

Hydroamination: Mercury(II) complexes are effective catalysts in hydroamination reactions, where an amine is added to an unsaturated carbon-carbon bond, such as an alkene or alkyne. This reaction is particularly valuable for synthesizing amines and nitrogen-containing heterocycles, compounds that are widely used in pharmaceuticals and agrochemicals. In the hydroamination of alkenes, mercury(II) complexes facilitate the activation of the alkene, making it more susceptible to nucleophilic attack by the amine. The reaction results in the formation of a new carbon-nitrogen (C-N) bond, which is a critical step in producing amine derivatives for drug development. The ability of mercury(II) to activate these substrates highlights its significance in this catalytic transformation [85]

Cyclization Reactions: Mercury(II) complexes serve as effective catalysts for cyclization reactions, where linear molecules are converted into cyclic structures, a crucial transformation in the synthesis of cyclic organic molecules like natural products and pharmaceuticals. For example, in the cyclization of dienes, mercury(II) complexes facilitate the formation of cyclic compounds by promoting the rearrangement of the linear diene structure. This process is particularly valuable in synthesizing natural products that feature ring systems, which are commonly found in biologically active compounds. Mercury's ability to activate such transformations underscores its utility in complex organic synthesis

Mercury(II) complexes are highly valued in catalysis due to their exceptional reactivity, enabling them to activate unreactive bonds and catalyze a wide range of organic transformations that may be challenging for other catalysts. Their stability in solution further enhances their utility in homogeneous catalysis, allowing for multiple catalytic cycles with minimal degradation, making them both efficient and cost-effective. Additionally, these complexes are versatile, finding application in various reactions such as oxidation, cross-coupling, hydroamination, and cyclization, making them indispensable in synthetic chemistry. A significant advantage is their ability to catalyze reactions under mild conditions, such as low temperatures or atmospheric pressure, making them ideal for industrial processes where energy efficiency and simplicity are critical**.**

Despite their catalytic potential, mercury(II) complexes face significant challenges. One of the primary concerns is their toxicity, as mercury is a well-known hazardous metal, posing environmental and health risks. The disposal of mercury-containing waste must be carefully managed, and residual mercury in final products is particularly problematic in sensitive areas like pharmaceuticals or food-related applications. Additionally, the limited commercial availability of many mercury(II) complexes means that researchers often need to synthesize them in the laboratory, which can impede their broader use, especially in industrial-scale processes. Another issue is the selectivity of mercury(II) complexes; while they are highly reactive, they may not always exhibit the desired selectivity, leading to side reactions or the formation of by-products that can reduce the overall efficiency of the catalytic process.

Research on mercury(II) complexes in catalysis continues to explore several promising avenues for future development. One key focus is the development of safer catalysts, driven by concerns about mercury's toxicity. Scientists are investigating alternatives using other transition metals like palladium, gold, and silver, which offer similar catalytic properties but with fewer environmental risks. Another area of interest is applying green chemistry principles to mercury(II)-catalyzed reactions, aiming to minimize waste, use non-toxic solvents, and enhance sustainability. Mechanistic studies are also being pursued to better understand the catalytic pathways of mercury(II) complexes, which could lead to the design of more efficient and selective catalysts. Additionally, researchers are working on expanding the scope of mercury(II) catalysis to new reactions, including photoredox catalysis and asymmetric synthesis, broadening the potential applications of these complexes in organic transformations.[86]

4.2.2.c) Material Science

Mercury(II) complexes have garnered interest in material science for their unique properties and versatile applications. Despite the toxic nature of mercury compounds, these complexes possess distinctive characteristics that make them valuable in the fabrication of advanced materials, including conducting polymers, nanocomposites, optoelectronic materials, and catalysts. This article explores the diverse applications of mercury(II) complexes in material science, their role in enhancing material properties, mechanisms of action, and the potential for future innovations in this interdisciplinary field.

Mercury(II) complexes consist of mercury in its +2 oxidation state, coordinated with various ligands that influence its chemical and physical properties. These complexes have found applications in different branches of material science due to their ability to form stable coordination frameworks, exhibit interesting electrical and optical properties, and interact with organic polymers and nanoparticles. Their potential in advanced material fabrication has been explored in fields such as electronics, nanotechnology, and energy storage, among others.

The development of mercury(II)-based materials has been spurred by the growing demand for novel materials with enhanced properties, including better conductivity, catalytic activity, and tunable optical characteristics. Mercury(II) complexes, with their unique chemical behavior and reactivity, have thus emerged as key components in the design of next-generation materials.

Mercury(II) complexes exhibit several important mechanisms that make them suitable for material fabrication. Some of these mechanisms include:

The coordination chemistry of mercury(II) plays a significant role in material science due to its ability to form stable bonds with a variety of ligands, such as nitrogen, oxygen, sulfur, and halogens. This versatility allows mercury(II) complexes to contribute to the development of extended coordination networks, which are essential for creating porous materials, frameworks, and other functional materials. Additionally, mercury(II)'s redox properties enable it to participate in electron transfer processes, crucial for designing materials used in energy storage, catalysis, and sensors. The optical and electronic properties of mercury(II) complexes, including tunable luminescence and charge transfer, make them valuable in optoelectronic devices and sensors, as the heavy metal character of mercury influences the bandgap and electronic structure of materials. Furthermore, mercury(II) complexes can interact with polymers and nanostructures, enhancing their properties by altering conductivity, mechanical strength, and stability, making them useful in advanced material applications.[87]

4.2.2.c.i) Applications in Conducting Polymers

Mercury(II) complexes are being investigated for their potential to enhance the electrical conductivity of polymers, which are crucial in the development of electronic devices, sensors, and energy storage systems. By incorporating mercury(II) complexes into the polymer matrix, the conductivity of the material can be significantly increased, thereby improving the performance of electronic components like transistors, diodes, and batteries. The enhancement mechanism involves the interaction of mercury(II) complexes with the π-conjugated system of the polymer, acting as a dopant that alters the electronic structure and facilitates charge transport. This doping process reduces the bandgap, leading to better conductivity and more efficient charge transfer. For instance, polyaniline, a well-studied conducting polymer, can be doped with mercury(II) complexes, resulting in materials with higher electrical performance, suitable for flexible electronics and wearable devices. Additionally, mercury(II) complexes can be incorporated into thin conductive films utilized in coatings, sensors, and photovoltaic devices, where controlling thickness and uniformity is vital for optimizing performance. Furthermore, by combining mercury(II) complexes with other conducting polymers, hybrid materials can be synthesized that exhibit enhanced properties, such as superior electrical conductivity, mechanical strength, and chemical stability. These hybrid materials hold promise for applications in high-performance batteries, supercapacitors, and flexible electronics

Nanocomposites are materials that integrate nanoparticles with a matrix material, typically a polymer or metal oxide, and the inclusion of mercury(II) complexes has demonstrated several advantageous properties. These complexes play a crucial role in the synthesis of metal nanoparticles, which are essential components of nanocomposites. The mercury(II) ion acts as a stabilizing agent during nanoparticle formation, controlling their size and shape, thereby tailoring the properties of the nanocomposites for specific applications such as catalysis, sensors, and drug delivery. For instance, mercury(II)-stabilized gold nanoparticles have been incorporated into polymer matrices to create nanocomposites with enhanced catalytic activity, which are particularly useful in environmental applications like pollutant degradation and toxic substance removal from water.

In addition to their role in nanoparticle synthesis, mercury(II) complexes enhance the mechanical and thermal properties of nanocomposites by forming strong bonds with the polymer matrix or interacting with the nanoparticles within the composite. This results in materials that exhibit greater resistance to mechanical stress and thermal degradation, essential for applications in aerospace, automotive, and energy storage systems. For example, mercury(II)-based nanocomposites have been developed with improved thermal stability for use in high-temperature environments, such as engine components or thermal insulation materials.

Moreover, the inclusion of mercury(II) complexes can significantly influence the optical and electronic properties of nanocomposites. These complexes may introduce luminescent or light-absorbing characteristics, making the nanocomposites suitable for optoelectronic devices like LEDs, solar cells, and photodetectors. An example includes nanocomposites containing mercury(II) complexes that have been utilized in the fabrication of light-emitting devices (LEDs) with tunable luminescence, which is vital for display technologies and lighting applications

Applications in Optoelectronic Materials: Mercury(II) complexes are being explored for their potential in optoelectronic materials, which are integral to devices that interact with light and electricity, such as photovoltaic cells, light-emitting diodes (LEDs), and photodetectors. Their ability to exhibit luminescence positions them as promising candidates for light-emitting devices. The emission properties of these complexes can be finely tuned by modifying the ligands or the coordination environment around the mercury center, a crucial aspect for developing LEDs that produce specific colors for display technologies and lighting applications. The luminescence arises from electronic transitions between the metal center and the ligands, allowing for controlled customization of the material's optical properties. For instance, mercury(II) complexes with phosphine ligands have been utilized to create LEDs emitting blue or green light, which are being investigated for use in high-efficiency displays and lighting systems.

Additionally, mercury(II) complexes have garnered attention for their role in photovoltaic materials, where their ability to absorb light and transfer electrons can be harnessed to enhance solar cell efficiency. By incorporating these complexes into the active layer of solar cells, researchers aim to improve light absorption and charge separation, ultimately leading to higher energy conversion efficiencies. An example includes mercury(II) complexes with sulfur-containing ligands, which have been investigated as light-harvesting materials in organic solar cells. These complexes demonstrate strong absorption in the visible range, making them suitable for enhancing the performance of next-generation solar technologies

Despite the promising applications of mercury(II) complexes in material science, there are several challenges that need to be addressed to fully realize their potential. The most significant challenge is the toxicity of mercury compounds, which poses environmental and health risks. Researchers are exploring ways to mitigate these risks, such as by developing less toxic mercury compounds, using mercury(II) complexes in confined environments, or replacing mercury with safer alternatives.[88]

4.2.2.d) Green Chemistry Approaches

Incorporating green chemistry principles into the design and synthesis of mercury(II)-based materials is an important area of research. This includes using non-toxic solvents, reducing the use of hazardous reagents, and developing recyclable materials. By making mercury(II) catalysis and material fabrication more environmentally friendly, researchers aim to broaden the applications of these materials while minimizing their impact on the environment.[89]

4.2.2.e) Expanding Applications in Energy Storage

The use of mercury(II) complexes in energy storage systems, such as batteries and supercapacitors, is a promising area of research. By leveraging the redox properties of mercury(II), researchers are exploring new ways to improve the energy density, cycle stability, and charging speed of these devices.

4.2.2.f) Integration with Emerging Technologies

The integration of mercury(II) complexes into emerging technologies, such as quantum dots, flexible electronics, and 3D-printed materials, offers exciting opportunities for the future. These technologies require materials with unique properties, such as tunable electronic behavior, high stability, and flexibility, which mercury(II) complexes can provide.

4.3. Applications of Iron(III) Complexes

4.3.1. Biological Applications

Iron(III) complexes have significant biological applications due to their essential role in various biochemical processes. These complexes mimic the active sites of metalloenzymes and are involved in electron transfer, oxygen transport, and catalysis in biological systems. One prominent application is their use as models for understanding the behavior of enzymes like catalase and peroxidase, which protect cells from oxidative stress by catalyzing the breakdown of hydrogen peroxide. Additionally, iron(III) complexes are explored for their potential in anticancer therapy, where they generate reactive oxygen species (ROS) to induce apoptosis in cancer cells. They are also investigated for their antimicrobial properties, where they disrupt bacterial cell metabolism by interfering with essential metal-dependent processes. Furthermore, iron(III) complexes serve as delivery agents for drugs and metal ions in therapeutic settings, enhancing the bioavailability of these compounds. Overall, they play a critical role in medical and biochemical research due to their versatile functions in biological systems.

4.3.1.a) Oxygen Transport

Oxygen transport and storage are vital functions in biological systems, primarily managed by metalloproteins like hemoglobin and myoglobin, which use iron as a central element to facilitate oxygen binding, transport, and release. Iron(III) complexes, which are central to these processes, have been the focus of significant research, especially for designing artificial hemoglobin and myoglobin systems in biotechnology. The development of artificial oxygen carriers mimicking the natural oxygen-binding properties of these proteins holds enormous potential in medical and industrial applications. This essay explores the role of iron(III) complexes in oxygen transport, their applications in biotechnology, the design of artificial hemoglobin and myoglobin, and challenges faced in the field.

Iron is an essential element for life, primarily because of its ability to readily transition between different oxidation states (Fe(II) and Fe(III)). This property makes iron crucial for various biological processes, particularly in oxygen transport. Hemoglobin (Hb) and myoglobin (Mb) are two iron-containing proteins responsible for oxygen transport and storage in mammals. Hemoglobin, found in red blood cells, transports oxygen from the lungs to tissues, while myoglobin, located in muscle tissues, stores and releases oxygen when needed.

Both hemoglobin and myoglobin use iron in their heme groups, a prosthetic group consisting of a porphyrin ring that coordinates an iron ion at its center. In hemoglobin and myoglobin, iron is in the Fe(II) oxidation state, which allows for reversible oxygen binding. When oxygen binds to the iron center, it forms an oxyhemoglobin or oxymyoglobin complex, which can be transported or stored until the oxygen is released to tissues.

The reversible nature of oxygen binding is due to iron's ability to switch between Fe(II) (ferrous) and Fe(III) (ferric) oxidation states. When oxygen binds to the Fe(II) center, it is oxidized to Fe(III), allowing the molecule to carry oxygen. Upon release of oxygen, the iron returns to its Fe(II) state. The dynamic balance between these oxidation states is crucial for effective oxygen transport and storage.

Given the essential role of iron in natural oxygen transport, researchers have sought to design artificial oxygen carriers that mimic the function of hemoglobin and myoglobin. These artificial oxygen carriers, or blood substitutes, are especially valuable in biotechnology and medicine, offering potential solutions for situations where blood transfusions are limited or unavailable. Iron(III) complexes have become a central focus of this research due to their ability to bind and release oxygen in a controlled and reversible manner.[91]

4.3.1.b) Applications in Biotechnology

Blood Substitutes: Artificial oxygen carriers based on iron(III) complexes are explored as blood substitutes for patients requiring transfusions. Such substitutes can reduce the dependence on human blood donations and prevent complications like blood type mismatches or infections. Hemoglobin-based oxygen carriers (HBOCs) and myoglobin-based analogs are among the prominent systems being studied.

Oxygen Therapy: Iron(III) complexes have potential applications in oxygen therapy, particularly in treating conditions where tissues suffer from low oxygen supply (hypoxia). By designing molecules that mimic the oxygen-binding properties of natural hemoglobin or myoglobin, researchers can create therapeutic agents that deliver oxygen directly to tissues.

Bioreactors and Industrial Processes: In biotechnology, iron(III) complexes can be used in bioreactors to facilitate oxygen transfer in biological reactions, particularly in large-scale fermentations or aerobic processes where controlled oxygen supply is essential for optimizing yields. Artificial oxygen carriers can enhance oxygen availability in industrial fermentation, enabling more efficient production of pharmaceuticals, biofuels, and other bioproducts.

Tissue Engineering and Regenerative Medicine: Oxygen availability is a critical factor in tissue engineering and regenerative medicine, as engineered tissues require a steady supply of oxygen for survival and growth. Iron(III) complexes could be incorporated into scaffolds or delivery systems to ensure adequate oxygen supply to engineered tissues, promoting cell proliferation and tissue regeneration.

Designing Iron(III) Complexes for Oxygen Transport

To design artificial oxygen carriers, researchers have focused on replicating the oxygen-binding mechanisms of natural hemoglobin and myoglobin. The primary challenge is to develop iron(III) complexes that can reversibly bind oxygen, similar to the heme group in natural proteins.

Ligand Design: In natural hemoglobin and myoglobin, the porphyrin ring plays a crucial role in stabilizing the iron center and facilitating oxygen binding. In artificial systems, researchers design ligands that mimic the porphyrin structure or use alternative ligands that stabilize the Fe(III) oxidation state while allowing for reversible oxygen binding. Chelating ligands, which bind to the iron center through multiple coordination sites, are often used to stabilize iron(III) complexes.

Oxygen Affinity: Artificial oxygen carriers must have the right balance of oxygen affinity to bind oxygen in high-oxygen environments (like the lungs) and release it in low-oxygen environments (like tissues). Too high

an affinity would prevent oxygen release, while too low an affinity would reduce the carrier's effectiveness. The ligand environment around the iron(III) center can be tuned to achieve the desired oxygen affinity.
Stability and Solubility: One of the challenges in designing artificial oxygen carriers is ensuring the stability of the iron(III) complex in biological environments. The complex must resist oxidation or degradation while maintaining solubility in aqueous environments, such as blood plasma. Hydrophilic ligands or encapsulation techniques are often employed to improve the solubility and biocompatibility of iron(III) complexes.
Oxygen Binding Kinetics: The rate at which an iron(III) complex binds and releases oxygen is critical for its function as an oxygen carrier. The kinetics of oxygen binding must be fast enough to allow for efficient oxygen loading and unloading during transport. Researchers study the coordination chemistry of iron(III) complexes to optimize oxygen-binding kinetics.

Despite the potential of iron(III) complexes in oxygen transport applications, several challenges must be addressed to make these systems viable for widespread use.
Iron is a redox-active metal, and uncontrolled release of iron can lead to the production of reactive oxygen species (ROS), which can damage cells and tissues. Careful control of the iron(III) complex's stability is necessary to prevent unwanted side effects. Encapsulation of iron(III) complexes within biocompatible materials, such as liposomes or polymers, is one approach to mitigate toxicity.
Artificial oxygen carriers must be biocompatible and non-immunogenic to avoid triggering an immune response. Modifications to the surface chemistry of iron(III) complexes or the use of inert carrier materials can help reduce immunogenicity.
For artificial oxygen carriers to be practical in medical or industrial applications, they must be cost-effective and scalable. The synthesis of iron(III) complexes and their incorporation into oxygen-delivery systems must be optimized for large-scale production.
In biological systems, hemoglobin and myoglobin are continuously regenerated. In artificial systems, iron(III) complexes must have a sufficient lifespan to function effectively over time without degradation or loss of activity.

Research into iron(III) complexes for oxygen transport is ongoing, with promising developments in both the medical and industrial fields. Advances in materials science, nanotechnology, and coordination chemistry are likely to drive the development of more effective and biocompatible artificial oxygen carriers. For example, the incorporation of iron(III) complexes into nanoparticles or hydrogels could enhance their stability, oxygen affinity, and release kinetics, making them more suitable for clinical use.
In the future, artificial oxygen carriers based on iron(III) complexes could provide life-saving alternatives in emergency medicine, surgery, and organ transplantation, where oxygen delivery is critical. Additionally, their use in tissue engineering and industrial biotechnology could open new avenues for innovation in oxygen-dependent processes.[92]

4.3.1.c) Antimicrobial Activity

Iron(III) complexes have garnered significant attention for their antimicrobial properties, positioning them as potential therapeutic agents in the battle against infectious diseases. The escalating issue of antibiotic resistance has intensified the search for alternative strategies to combat bacterial and fungal infections. Given their versatility and biological relevance, iron(III) complexes are promising candidates for antimicrobial therapy. These complexes interact with microbial cells in various ways, often inducing oxidative stress, disrupting cellular structures, and inhibiting enzymatic functions. The growing global challenge of antimicrobial resistance (AMR) poses a significant threat to public health, with multidrug-resistant (MDR) bacteria rendering traditional antibiotics less effective and leading to increased morbidity, mortality, and healthcare costs. Notorious MDR pathogens like *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*, along with resistant fungal pathogens such as *Candida* species, highlight the urgent need for novel antimicrobial agents with unique mechanisms of action.
Iron(III) complexes exploit the vulnerabilities of microorganisms by interfering with essential biological processes. Their antimicrobial activity manifests through several mechanisms, depending on their structure, coordination environment, and biological interactions. A primary mechanism is the generation of reactive oxygen species (ROS), which occurs through iron's redox cycling between Fe(II) and Fe(III), facilitating Fenton-like reactions that produce highly reactive hydroxyl radicals. This oxidative damage affects crucial biomolecules like DNA, proteins, and lipids, ultimately leading to cell death, particularly in bacteria vulnerable to oxidative stress. Additionally, iron(III) complexes can interact with microbial DNA through intercalation or coordination with the phosphate backbone, inhibiting replication and transcription, thereby hindering cellular growth. They may also disrupt essential metabolic processes by inhibiting metalloenzymes, as iron(III) can coordinate with their active sites.[93]

Moreover, certain iron(III) complexes can compromise microbial cell membranes by interacting with phospholipids and other membrane components, increasing permeability and causing leakage of essential ions and molecules, which results in cell death. This mechanism is notably effective against Gram-negative bacteria, which possess a protective outer membrane. Another crucial aspect of their antimicrobial action is metal ion deprivation; iron is a vital nutrient for microbial growth. Many bacteria employ high-affinity iron acquisition systems, such as siderophores, to extract iron from their environment. Iron(III) complexes can sequester iron, rendering it unavailable to bacteria, thereby inducing "iron starvation." This weakens bacterial defenses and makes them more susceptible to oxidative stress and immune responses, as some iron(III) complexes mimic bacterial siderophores, tricking bacteria into internalizing them and subsequently releasing toxic iron levels or generating ROS within the cell.

The efficacy of iron(III) complexes extends to both bacterial and fungal pathogens. These complexes have demonstrated broad-spectrum antimicrobial activity, showing effectiveness against both Gram-positive and Gram-negative bacteria, as well as antifungal properties against pathogenic fungi. For Gram-positive bacteria like *Staphylococcus aureus* and *Bacillus subtilis*, the thick peptidoglycan layer provides rigidity, yet iron(III) complexes can penetrate and exert their effects through ROS generation and enzyme inhibition. For instance, iron(III)-salen complexes have exhibited potent antibacterial activity against methicillin-resistant *Staphylococcus aureus* (MRSA). In contrast, Gram-negative bacteria, such as *Escherichia coli* and *Pseudomonas aeruginosa*, often exhibit greater resistance due to their double-membrane structure. However, some iron(III) complexes, particularly those with Schiff bases or nitrogen-containing heterocycles, have shown the capability to disrupt these membranes and inhibit essential metabolic pathways.

Fungal infections, especially those caused by *Candida* species, pose significant risks to immunocompromised individuals. Iron(III) complexes have demonstrated promising antifungal activity by compromising the integrity of the fungal cell wall and membrane. Iron(III)-based chelates have been studied for their ability to inhibit fungal growth through iron sequestration, which is vital for fungal metabolism. Furthermore, ROS generated by iron(III) complexes can lead to oxidative damage, contributing to the destruction of fungal cells. Overall, the unique mechanisms of action and broad-spectrum efficacy of iron(III) complexes underscore their potential as innovative antimicrobial agents in addressing the pressing challenge of antibiotic resistance.[94]

4.3.1.d) Applications in Medicine

The antimicrobial properties of iron(III) complexes have opened up several potential applications in medicine, particularly for treating bacterial and fungal infections and developing novel therapeutic strategies. One promising application is their incorporation into topical formulations for treating skin infections, wounds, and burns. Due to their ability to generate reactive oxygen species (ROS) and disrupt microbial membranes, iron(III) complexes can effectively prevent infections caused by both bacteria and fungi. This localized application reduces the risk of systemic toxicity, making it a viable option for targeted treatment.

Additionally, there is a growing interest in developing antibacterial coatings for medical devices such as catheters, prosthetics, and surgical implants. By embedding iron(III) complexes into polymer coatings, these devices can benefit from long-lasting antimicrobial protection against biofilm formation and device-related infections. The ability of these complexes to release ROS upon contact with microbial cells further enhances their suitability for such applications.

Moreover, iron(III) complexes can be employed in combination therapies alongside traditional antibiotics to boost their efficacy. Targeting different bacterial pathways allows these complexes to overcome resistance mechanisms and improve overall therapeutic outcomes. For instance, iron(III) complexes that generate ROS can synergistically work with antibiotics that disrupt cell wall synthesis, leading to more effective bacterial killing.

In the realm of antifungal treatments, iron(III) complexes are also being explored as potential agents for systemic fungal infections. Their ability to sequester iron and generate ROS makes them effective at killing fungal cells, which rely on iron for growth and virulence. These complexes can be formulated into antifungal creams, gels, or oral medications for treating infections such as candidiasis. Overall, the diverse applications of iron(III) complexes highlight their potential as innovative therapeutic agents in the fight against infectious diseases

Despite their promising antimicrobial activity, iron(III) complexes face several challenges in their development as therapeutic agents. One significant concern is their potential toxicity to human cells. The reactive oxygen species (ROS) that effectively kill microbial cells can also damage host tissues, leading to oxidative stress and inflammation. To mitigate this issue, researchers are exploring strategies to control ROS production, such as using targeted delivery systems or designing complexes that activate only in the presence of microbial enzymes.

Another challenge is the stability of iron(III) complexes in biological environments. These complexes can undergo rapid degradation or reduction, limiting their effectiveness. To enhance stability and prolong antimicrobial activity, the development of more stable complexes or the use of protective carriers like liposomes or nanoparticles is being investigated.

Achieving selective targeting of microbial cells without harming host tissues presents another hurdle. While some iron(III) complexes can preferentially accumulate in bacterial or fungal cells, further research is needed to optimize their selectivity and minimize off-target effects.

Additionally, there is a risk of bacteria developing resistance to iron(III) complexes over time, despite their distinct mechanisms of action compared to traditional antibiotics. Ongoing research is focused on understanding the potential for resistance and developing strategies to minimize it. Addressing these challenges is crucial for the successful translation of iron(III) complexes into effective therapeutic agents[95]

Future Directions:

The field of iron(III) complexes as antimicrobial agents is still in its early stages, but there is significant potential for further development. Future research is likely to focus on designing novel ligands to enhance the selectivity, stability, and antimicrobial activity of these complexes. Additionally, exploring synergistic therapies by combining iron(III) complexes with other antimicrobial agents could improve efficacy and reduce the development of resistance. Another promising avenue is the utilization of nanotechnology for targeted delivery systems, which would enable the direct delivery of iron(III) complexes to the site of infection, thereby minimizing systemic toxicity. These strategies could pave the way for the effective application of iron(III) complexes in antimicrobial therapy

4.3.1.e) The Role of Iron in Cancer Cell Biology

Iron is an essential element for various cellular processes, including DNA synthesis, cellular respiration, and cell cycle progression. Cancer cells, due to their high proliferative capacity, exhibit an increased demand for iron to support their metabolic activities. To meet this requirement, cancer cells upregulate several iron acquisition mechanisms, including the expression of transferrin receptors (TfR1), divalent metal transporter 1 (DMT1), and ferritin. The overexpression of TfR1 on the surface of cancer cells, in particular, has been observed in numerous malignancies, including breast, prostate, liver, and colorectal cancers.

The transferrin receptor plays a key role in cellular iron uptake by binding to transferrin, an iron-binding glycoprotein present in the bloodstream. Once transferrin binds to TfR1 on the cell surface, the receptor-ligand complex is internalized through receptor-mediated endocytosis, delivering iron into the cell. This pathway offers an ideal opportunity to exploit cancer cells' heightened need for iron by conjugating therapeutic agents with transferrin or iron(III) complexes, allowing for selective targeting of cancer cells.[96]

4.3.1.f) Iron(III) Complexes in Drug Delivery

Iron(III) complexes have unique chemical properties that make them suitable for drug delivery systems. Iron can exist in multiple oxidation states, which allows for controlled release of drugs under physiological conditions. Additionally, iron(III) complexes can be synthesized with various ligands to improve their stability, solubility, and targeting capabilities. By combining these features with the cancer cells' dependence on iron, researchers have developed iron(III) complexes that can deliver anticancer drugs directly to tumor cells, thereby reducing side effects and improving treatment outcomes.

The development of iron(III)-based drug delivery systems typically involves conjugating iron(III) to a therapeutic agent, a targeting ligand (such as transferrin or other molecules that bind to TfR1), and a stabilizing component (such as a polymer or nanoparticle). The goal is to achieve selective uptake by cancer cells via transferrin receptor-mediated endocytosis, followed by the release of the drug inside the cell.

The mechanism of targeting cancer cells through transferrin receptors with iron(III) complexes relies on the established process of transferrin-mediated iron uptake. Initially, transferrin, loaded with iron(III), binds to the transferrin receptor (TfR1) on the surface of cancer cells. Cancer cells overexpress TfR1, which allows for a higher affinity for transferrin compared to normal cells, ensuring selective targeting. Following this binding, the transferrin-iron(III) complex is internalized through clathrin-mediated endocytosis, forming an endosome within the cancer cell. The acidic environment of the endosome triggers the dissociation of iron from transferrin. Inside the endosome, iron is reduced from Fe(III) to Fe(II) by endosomal ferrireductases and is subsequently released into the cytoplasm via DMT1. Simultaneously, the therapeutic agent conjugated to the iron(III) complex is released, allowing it to exert its cytotoxic effects. Depending on the nature of the therapeutic agent, this can lead to apoptosis, inhibition of cell division, or oxidative stress, resulting in cancer cell death. The selective uptake of the drug by cancer cells minimizes damage to healthy tissues, thereby reducing systemic toxicity. There are several classes of iron(III) complexes that have been explored for drug delivery purposes, each with distinct chemical properties and targeting mechanisms.

Iron(III)-Transferrin Complexes: One of the most direct approaches for targeted drug delivery is to use transferrin itself as the targeting ligand. In this system, therapeutic agents are conjugated to transferrin or iron(III)-loaded transferrin molecules, which then bind to TfR1 on cancer cells. Once internalized, the therapeutic agent is released within the tumor cell, allowing for targeted treatment. This approach has been explored for the delivery of chemotherapeutic agents such as doxorubicin and cisplatin. Iron(III)-transferrin-doxorubicin conjugates have been developed to selectively deliver the drug to cancer cells. Doxorubicin is a potent chemotherapeutic agent, but its use is limited by systemic toxicity. By conjugating it to iron(III)-transferrin, researchers have shown enhanced uptake by cancer cells and reduced off-target effects.

Iron(III) Nanoparticles: Iron(III) oxide nanoparticles ($Fe3O4$), also known as magnetite nanoparticles, are widely used in drug delivery due to their biocompatibility, magnetic properties, and ability to be functionalized with targeting ligands. These nanoparticles can be coated with transferrin or other targeting molecules to enhance their uptake by cancer cells via TfR1-mediated endocytosis. Additionally, the magnetic properties of these nanoparticles enable their use in magnetic resonance imaging (MRI) for diagnostic purposes, providing a dual-function system for both drug delivery and tumor imaging. Transferrin-coated iron oxide nanoparticles have been developed for the delivery of anticancer drugs such as paclitaxel. In preclinical studies, these nanoparticles have shown enhanced tumor targeting and improved drug efficacy compared to free drug administration.[97]

Iron(III) can form coordination complexes with various ligands, including Schiff bases, porphyrins, and other organic molecules. These complexes are highly versatile and can be modified to improve their solubility, stability, and targeting capabilities. Iron(III)-based coordination complexes can be conjugated to therapeutic agents or loaded with drugs to enhance their delivery to cancer cells. Iron(III)-Schiff base complexes have been studied for their potential as anticancer agents. By conjugating these complexes to transferrin, researchers have achieved selective targeting of cancer cells and demonstrated significant cytotoxic effects against tumor cells in vitro.

Iron chelators are small molecules that bind tightly to iron ions, forming stable complexes. Iron(III) chelators have been used to deprive cancer cells of iron, inhibiting their growth and proliferation. However, these chelators can also be used as drug delivery vehicles. By loading drugs onto iron(III)-chelating agents, researchers can target cancer cells via their iron acquisition pathways. Deferoxamine, an iron(III) chelator, has been conjugated to anticancer drugs to enhance their delivery to tumor cells. This approach exploits the cancer cells' dependence on iron, allowing for selective drug uptake.

The use of iron(III) complexes in drug delivery presents several advantages, particularly in the realm of cancer therapy. One key benefit is targeted delivery; iron(III) complexes can exploit the overexpression of transferrin receptors on cancer cells, enabling selective drug delivery while minimizing off-target effects on healthy tissues. This selectivity is crucial for reducing the side effects often associated with chemotherapy, which can damage rapidly dividing cells in the bone marrow, gastrointestinal tract, and hair follicles. Additionally, iron(III) complexes can be engineered to facilitate controlled drug release in response to specific stimuli, such as changes in pH or redox conditions. This characteristic allows for the release of therapeutic agents precisely within the tumor microenvironment, which is typically more acidic than surrounding tissues.

Moreover, iron(III) complexes, particularly iron oxide nanoparticles, offer multifunctionality, serving both therapeutic and diagnostic purposes. This dual functionality paves the way for the development of theranostic agents that combine drug delivery with imaging techniques, such as MRI or fluorescence imaging. Biocompatibility is another advantage, as iron is a naturally occurring element in the human body, making iron(III) complexes generally well-tolerated and posing a low risk of eliciting immune responses. Excess iron can be safely stored in ferritin or excreted from the body, further reducing the risk of toxicity. Lastly, iron(III) complexes hold promise in overcoming drug resistance, a common challenge in cancer treatment. By delivering drugs through these complexes, researchers can circumvent some resistance mechanisms, enhancing treatment efficacy. For instance, iron(III)-based drug delivery systems can facilitate drug uptake, thereby improving therapeutic outcomes

4.3.1.g) Iron(III) Complexes as MRI Contrast Agents

Magnetic Resonance Imaging (MRI) is a non-invasive imaging technique widely used in medical diagnostics to visualize internal organs, tissues, and structures with high resolution. MRI relies on the behavior of hydrogen protons in the body's tissues when exposed to a strong magnetic field and radiofrequency pulses. To improve the quality and contrast of MRI images, contrast agents are often administered to patients. These agents alter the magnetic properties of nearby hydrogen nuclei, enhancing signal differences between tissues and improving diagnostic accuracy. Iron(III) complexes have gained attention as potential MRI contrast agents due to their unique magnetic properties, biocompatibility, and ability to be functionalized for targeted imaging.

This essay will discuss the mechanisms by which MRI contrast agents work, the advantages and challenges of using iron(III) complexes in MRI, and recent developments in iron(III)-based contrast agents. The quality of an MRI image depends on the relaxation properties of hydrogen protons in water molecules. When exposed to a magnetic field, these protons align with or against the field, creating a net magnetization. Radiofrequency pulses disturb this alignment, and as the protons return to their equilibrium state, they emit signals that are captured to form an image. The relaxation process occurs in two phases:

T1 relaxation, also known as longitudinal relaxation, refers to the time required for protons to realign with the magnetic field after being disturbed. This process influences the signal intensity and brightness of the MRI image; shorter T1 relaxation times lead to brighter images. In contrast, T2 relaxation, or transverse relaxation, pertains to the loss of coherence among spinning protons, resulting in signal decay. T2 relaxation plays a critical role in determining tissue contrast, with longer T2 relaxation times producing darker images. MRI contrast agents function by modifying the T1 or T2 relaxation times of water protons in various tissues. Most contrast agents are classified as either T1 or T2 agents. T1 contrast agents, such as gadolinium-based compounds, work by shortening the T1 relaxation time, which enhances the brightness of the images and is commonly used for highlighting soft tissues and blood vessels. On the other hand, T2 contrast agents, including iron-based nanoparticles, decrease the T2 relaxation time, resulting in darker areas in the images, making them useful for imaging tumors or identifying abnormalities in the liver and spleen. Iron(III) complexes, especially as iron oxide nanoparticles, have predominantly been explored as T2 contrast agents, though recent advancements have also investigated their potential as T1 agents. The following sections will discuss the advantages and limitations of iron(III)-based contrast agents and their evolving role in MRI.

Iron(III) complexes, particularly those involving iron oxide nanoparticles, offer several advantages over traditional gadolinium-based contrast agents:

Iron is an essential element in the human body, playing a crucial role in oxygen transport, enzyme activity, and cellular metabolism. The body has natural mechanisms for processing and storing excess iron, making iron(III) complexes inherently biocompatible. Iron oxide nanoparticles, in particular, can be broken down and metabolized into ferritin, the body's iron storage protein, reducing the risk of toxicity. This makes iron(III)-based contrast agents more favorable for long-term safety compared to gadolinium-based agents, which can accumulate in tissues and pose risks such as nephrogenic systemic fibrosis (NSF) in patients with impaired kidney function.[98]

Iron(III) in the form of iron oxide (Fe_3O_4 or γ-Fe_2O_3) nanoparticles exhibits superparamagnetic properties, meaning they become highly magnetized in the presence of an external magnetic field but lose their magnetism once the field is removed. This superparamagnetism enhances the T2 relaxation effect, leading to significant signal decay and high contrast between tissues in MRI scans. The ability of iron oxide nanoparticles to generate strong magnetic moments makes them highly effective at altering the local magnetic field, improving contrast sensitivity and providing clearer images for diagnosis.

Iron(III)-based contrast agents can be functionalized with various coatings, targeting ligands, or therapeutic molecules, enabling them to serve multiple purposes beyond imaging. For example, iron oxide nanoparticles can be coated with polyethylene glycol (PEG) or dextran to improve their stability and biocompatibility. Additionally, they can be conjugated with antibodies, peptides, or small molecules to specifically target tumors, inflamed tissues, or areas of infection. This multifunctionality opens up possibilities for theranostics, where the same agent can be used for both imaging and therapy, such as delivering drugs or generating localized heat (hyperthermia) for cancer treatment.

Iron oxide nanoparticles can be engineered to have long circulation times in the bloodstream, allowing for extended imaging windows and the possibility of repeated imaging without the need for multiple injections. By modifying the surface chemistry of the nanoparticles, researchers can reduce uptake by the reticuloendothelial system (RES) and improve their biodistribution, making them more effective for imaging vascular structures, tumors, and other regions of interest.

Iron-based contrast agents are generally safer for patients with renal impairment. In contrast, gadolinium-based agents pose a risk of gadolinium deposition in tissues and organs, which can lead to adverse effects, particularly in patients with chronic kidney disease. The natural metabolism and excretion pathways for iron reduce the likelihood of long-term toxicity, making iron(III) complexes a safer alternative, particularly for patients with compromised kidney function.

Most iron(III)-based MRI contrast agents function as T2 agents, which cause signal hypointensity (darkening) in MR images. These agents are especially useful for imaging highly vascularized tissues, tumors, and certain organs such as the liver and spleen.

Iron oxide nanoparticles (IONPs) are the most extensively studied class of iron-based T2 contrast agents. Typically consisting of a core of iron(III) oxide (magnetite or maghemite) coated with various biocompatible materials to enhance stability and prevent aggregation, IONPs have tunable size, shape, and surface chemistry, which can be precisely controlled to optimize their performance as MRI contrast agents. Superparamagnetic iron oxide nanoparticles (SPIONs) are small enough to exhibit superparamagnetism, a property that significantly enhances their ability to shorten T2 relaxation times and generate high contrast in MRI images. SPIONs are utilized for imaging liver lesions, detecting lymph node metastasis, and monitoring inflammation, as their small size allows them to circulate in the bloodstream and be taken up by macrophages in inflamed tissues or tumors. Ultra-small superparamagnetic iron oxide nanoparticles (USPIOs) are even smaller than SPIONs, typically less than 50 nm in diameter. Their diminutive size results in longer blood circulation times and the ability to pass through smaller capillaries, making them suitable for imaging the brain and detecting areas of neuroinflammation. USPIOs are being investigated for applications in imaging neurodegenerative diseases, including multiple sclerosis and Alzheimer's disease.

Iron oxide nanoparticles have received approval for various clinical applications in MRI, especially for imaging the liver and spleen, where they are taken up by the reticuloendothelial system (RES), enabling detailed imaging of these organs. In liver and spleen imaging, iron oxide nanoparticles are internalized by Kupffer cells in the liver and macrophages in the spleen, providing contrast between healthy tissue and areas affected by tumors or other pathologies. This capability is particularly valuable in detecting hepatic metastases and other liver lesions that are challenging to visualize with traditional MRI techniques. Additionally, due to their abnormal vascularization, increased permeability, and inflammation, tumors serve as suitable targets for iron oxide nanoparticles. By accumulating in the tumor microenvironment, these nanoparticles create dark contrast regions in T2-weighted images, facilitating tumor detection and characterization.

While iron(III) complexes have been predominantly used as T2 contrast agents, recent research has shifted towards the development of iron-based T1 contrast agents, which produce hyperintense (bright) signals in MRI images. These agents are particularly useful for imaging blood vessels, brain structures, and soft tissues. The development of iron-based T1 agents seeks to provide a safer alternative to gadolinium-based agents, which have been associated with toxicity concerns. Gadolinium-based contrast agents (GBCAs) are the most widely used T1 agents; however, they pose risks such as nephrogenic systemic fibrosis and gadolinium deposition in the brain. Iron-based T1 agents present a safer alternative, particularly for patients with renal impairment. One example is manganese-doped iron oxide nanoparticles, which have been developed to exhibit both T1 and T2 contrast-enhancing properties. By incorporating manganese, which has paramagnetic properties akin to gadolinium, these nanoparticles can shorten T1 relaxation times and produce bright images, allowing for a dual-modality imaging approach. Additionally, iron(III) complexes with organic chelating ligands have been explored as potential T1 contrast agents, designed to shorten the T1 relaxation time of nearby water protons, thus providing bright contrast in MRI images. While the design of these complexes is still in the experimental phase, they hold promise for future clinical applications.

.

Challenges and Future Directions: Despite their potential, iron(III) complexes as MRI contrast agents face several challenges. One significant issue is the optimization of relaxation properties; developing iron-based agents with strong T1 contrast while minimizing T2 effects remains difficult. Achieving the right balance between particle size, shape, and surface chemistry is crucial for optimizing their performance. Additionally, while iron oxide nanoparticles can be functionalized with targeting ligands, achieving precise targeting and accumulation in specific tissues is still a challenge. Improving targeting efficiency will enhance the diagnostic potential of these agents. Another concern is toxicity and clearance; although iron is generally more biocompatible than gadolinium, high doses of iron-based agents may still lead to toxicity. Ensuring that these agents are efficiently cleared from the body is essential for their long-term safety. Finally, while many iron-based contrast agents show promise in preclinical studies, translating these agents to clinical practice requires rigorous testing, regulatory approval, and large-scale production.

4.3.2.) General Applications:

4.3.2.a) Catalysis

Iron(III) complexes are highly versatile and valuable in catalysis, offering numerous advantages in various organic reactions. As a transition metal, iron is relatively abundant, inexpensive, and environmentally friendly, making it a sustainable choice for catalytic applications. Iron(III) complexes, in particular, have garnered significant attention in catalysis due to their ability to facilitate a wide range of reactions, including oxidation, polymerization, C–C bond formation, and other important transformations in synthetic chemistry. The use of iron-based catalysts in green chemistry initiatives has further solidified their role in both academic research and industrial processes.

This essay provides a detailed overview of the catalytic applications of iron(III) complexes, including their role in oxidation reactions, polymerization, and various other organic transformations, alongside a discussion on the advantages and challenges associated with their use.

Oxidation Reactions

a. Oxidation of Organic Substrates: Iron(III) complexes play a prominent role in oxidation reactions, which are crucial in organic synthesis for converting hydrocarbons into more functionalized products, such as alcohols, ketones, aldehydes, and carboxylic acids. Iron(III)-catalyzed oxidation reactions are typically achieved using oxidants like hydrogen peroxide (H_2O_2), oxygen (O_2), or other peroxides. Iron(III) complexes are particularly useful due to their ability to cycle between oxidation states (Fe(II)/Fe(III)), facilitating electron transfer processes that drive oxidation.

One classic example is the iron(III)-catalyzed oxidation of alcohols to aldehydes and ketones. The high efficiency of iron(III) complexes as catalysts in these reactions is attributed to their ability to activate hydrogen peroxide, leading to the formation of highly reactive iron-oxo species. These intermediates are responsible for the selective oxidation of alcohols without overoxidation to carboxylic acids.[99]

b. Biomimetic Oxidation Catalysis: Iron(III) complexes have been employed as biomimetic catalysts, mimicking the behavior of natural iron-containing enzymes, such as cytochrome P450, which catalyze the oxidation of organic substrates in biological systems. These biomimetic catalysts are inspired by the natural coordination environment of the iron centers in these enzymes, often using porphyrin or non-heme ligands to stabilize the iron(III) complex and mimic the active site of the enzyme.

For instance, iron(III)-porphyrin complexes have been widely studied for their ability to catalyze the selective oxidation of hydrocarbons and olefins, much like cytochrome P450 enzymes do in nature. These systems have shown potential in the oxidation of alkanes and alkenes, which are otherwise difficult to oxidize under mild conditions. The biomimetic approach not only provides a framework for developing environmentally friendly oxidation processes but also contributes to the understanding of biological oxidation mechanisms.

c. Catalytic Activation of Oxygen: The ability of iron(III) complexes to activate molecular oxygen (O_2) for oxidation reactions is of great interest in both academic and industrial settings. Iron complexes can activate oxygen to produce reactive oxygen species (ROS), such as superoxide and peroxide, which can then participate in oxidative transformations. This catalytic activation of oxygen is crucial for green chemistry because it uses a cheap, abundant, and environmentally benign oxidant.

A notable example of oxygen activation is the iron(III)-catalyzed epoxidation of alkenes, where iron(III) complexes activate oxygen or hydrogen peroxide to oxidize alkenes into epoxides. Epoxides are valuable intermediates in the synthesis of various pharmaceuticals, agrochemicals, and polymers. Iron-catalyzed epoxidation reactions are advantageous due to their high selectivity and the ability to operate under mild conditions.

Polymerization Reactions

Iron(III) complexes also serve as catalysts in polymerization reactions, where they play a role in the synthesis of polymers through the formation of macromolecular chains from monomer units. The catalytic activity of iron(III) complexes in polymerization is particularly valuable in industrial applications due to their cost-effectiveness and the potential for developing more sustainable polymerization processes.

a. Ring-Opening Polymerization (ROP): One of the significant applications of iron(III) complexes is in ring-opening polymerization (ROP), which involves the conversion of cyclic monomers into linear polymers. Iron(III) complexes have been successfully employed as catalysts for the ROP of lactones and lactides, which are precursors to biodegradable polymers, such as polyesters and polylactides (PLA). These biodegradable polymers are of particular interest in the production of environmentally friendly plastics and medical materials, such as surgical sutures and drug delivery systems.

Iron(III) complexes provide several advantages in ROP, including the ability to catalyze polymerization under mild conditions, high catalytic efficiency, and the production of well-defined polymers with controlled molecular weights and low polydispersity. Furthermore, the non-toxic nature of iron makes it an attractive alternative to other metal catalysts used in polymerization, such as tin or aluminum complexes, which can pose environmental and health risks.

b. Coordination Polymerization: Iron(III) complexes are also involved in coordination polymerization, a process that forms polymers by coordinating monomers to a metal center. In the case of iron(III) complexes, the metal center can coordinate with olefin or diene monomers, facilitating their polymerization into linear or branched polymers. Iron(III) complexes are particularly useful in the polymerization of ethylene and propylene, two of the most common monomers used in the production of plastics.

The use of iron-based catalysts in coordination polymerization is part of a broader effort to develop more sustainable and environmentally friendly catalysts for the production of polyolefins. Iron catalysts are less expensive and less toxic than traditional catalysts, such as those based on platinum or nickel, making them a viable option for large-scale industrial applications.

c. Atom Transfer Radical Polymerization (ATRP): Iron(III) complexes have been investigated as catalysts for atom transfer radical polymerization (ATRP), a controlled radical polymerization technique that allows for the precise control of polymer architecture, including block copolymers, star-shaped polymers, and graft polymers. ATRP is widely used in the production of advanced polymer materials with specific properties, such as thermal stability, mechanical strength, and chemical resistance.

Iron-based ATRP catalysts are gaining attention because they offer a more environmentally benign alternative to traditional copper-based catalysts, which can leave behind toxic residues in the final polymer product. Iron(III) complexes in ATRP exhibit high catalytic activity and excellent control over polymerization, enabling the synthesis of well-defined polymers with desired properties.

Cross-Coupling Reactions

Cross-coupling reactions are fundamental in organic synthesis for forming carbon-carbon (C–C) and carbon-heteroatom (C–X) bonds, which are essential in the construction of complex organic molecules, including pharmaceuticals, agrochemicals, and natural products. Iron(III) complexes have emerged as promising catalysts for a variety of cross-coupling reactions, offering a greener and more cost-effective alternative to traditional palladium or platinum-based catalysts.

a. Iron-Catalyzed C–C Bond Formation: Iron(III) complexes are widely employed in cross-coupling reactions involving C–C bond formation, such as the Kumada, Negishi, and Suzuki–Miyaura reactions. These reactions are typically used to couple aryl halides with organometallic reagents, forming biaryl compounds that are key intermediates in drug synthesis and materials science. The use of iron(III) complexes in these reactions is attractive due to the low cost of iron and the ability to operate under milder conditions compared to other transition metals. Recent advances have demonstrated that iron(III) complexes can achieve high catalytic activity and selectivity in cross-coupling reactions, rivaling traditional palladium-based catalysts. The development of ligands that stabilize the iron center and promote efficient electron transfer has been key to improving the performance of iron-catalyzed cross-coupling reactions.

b. Iron-Catalyzed C–X Bond Formation: In addition to C–C bond formation, iron(III) complexes are effective catalysts for the formation of C–X bonds (where X = O, N, S, etc.). These reactions are important for the synthesis of a wide range of functionalized organic compounds, including ethers, amines, and sulfides. Iron-catalyzed C–O and C–N bond-forming reactions, in particular, have gained attention due to their relevance in the synthesis of pharmaceuticals and natural products.

The ability of iron(III) complexes to catalyze C–X bond formation with high selectivity and efficiency is attributed to their ability to stabilize reactive intermediates and promote electron transfer processes. This makes iron-catalyzed cross-coupling reactions a valuable tool in synthetic organic chemistry.

Green Chemistry and Sustainable Catalysis

The use of iron(III) complexes in catalysis aligns with the principles of green chemistry, which aim to reduce the environmental impact of chemical processes by minimizing waste, energy consumption, and the use of hazardous substances. Iron is an abundant and non-toxic metal, making it an ideal candidate for developing sustainable catalytic processes.

Iron(III) complexes have been employed in a wide range of green catalytic processes, including the oxidation of organic substrates with environmentally benign oxidants like hydrogen peroxide or oxygen, as well as in polymerization reactions that produce biodegradable plastics. The ability to recycle iron-based catalysts and the use of non-toxic ligands further enhance the sustainability of these processes.

Despite their advantages, the use of iron(III) complexes in catalysis is not without challenges. One of the main limitations is the potential for catalyst deactivation, which can occur due to the formation of inactive iron species during the reaction. Developing more stable iron(III) complexes with robust ligands that can withstand harsh reaction conditions is an ongoing area of research.

Additionally, while iron(III) complexes have shown great promise in a variety of catalytic applications, their catalytic activity and selectivity may still lag behind those of precious metal catalysts in some cases. Further research is needed to optimize the performance of iron(III) catalysts and expand their application to new types of reactions.

4.3.2.b) Dyes and Pigments:

Iron(III) complexes have gained significant attention in various industries, particularly in textiles and paints, due to their vivid colors and stability. These complexes provide a wide range of hues and properties that make them suitable as colorants. This article explores the applications, mechanisms, and advantages of using iron(III) complexes in the dyeing and pigmentation processes, along with considerations regarding their environmental impact and future directions.

Dyes and pigments are essential components in many industries, serving to impart color to textiles, paints, coatings, plastics, and other materials. Dyes are typically soluble in the medium in which they are applied, allowing them to bond with the substrate, while pigments are insoluble particles that provide color through dispersion. The choice of colorant significantly influences the aesthetic appeal, durability, and performance of the final product.

The growing demand for sustainable and environmentally friendly colorants has spurred interest in natural and inorganic alternatives, including iron(III) complexes. These complexes are recognized for their vibrant colors, stability, and versatility in various applications.

Iron(III) complexes are formed when iron(III) ions coordinate with various ligands, such as organic acids, phenols, or nitrogen-containing compounds. The nature of the ligand and the coordination environment around the iron ion significantly influence the color and stability of the complex. Common ligands used to form iron(III) complexes for coloring applications include salts of organic acids, such as acetic acid, citric acid, and tannins, which can form stable complexes with iron(III) ions, imparting color and improving solubility. Phenolic compounds also play a role, as they can form chelate complexes with iron(III), leading to vivid colors due to charge transfer and electronic transitions. Additionally, amino acids and peptides can act as ligands, resulting in iron(III) complexes with distinct colors suitable for various applications.

The colors produced by iron(III) complexes range from bright yellows to deep reds and browns, depending on the ligand used and the coordination geometry. The distinct color characteristics arise from electronic transitions within the iron ion and ligand-to-metal charge transfer processes. The presence of different ligands and oxidation states of iron can further tune the hue of the complexes.

The textile industry has a long-standing history of using dyes to color fabrics and fibers. Iron(III) complexes have emerged as valuable colorants due to their excellent performance in dyeing processes.

Iron(III) complexes can be used in natural dyeing processes, where they serve as mordants to enhance the color uptake of natural dyes. Mordants are substances that fix dyes to the fabric by forming coordination complexes with the dye molecules. The use of iron(III) as a mordant can lead to rich, deep colors, particularly when combined with natural dyes derived from plants, insects, or minerals.

For example, iron(III) can enhance the color of dyes from madder root (Rubia tinctorum) and weld (Reseda luteola) when applied to cotton or wool fabrics. The resulting shades can range from earthy browns to deep reds, making iron(III) complexes highly desirable in traditional and artisanal dyeing practices.

In synthetic dyeing processes, iron(III) complexes can be employed as standalone dyes or as components in dye formulations. These complexes can be used to dye a wide variety of fibers, including cotton, silk, wool, and synthetic materials. The stability of iron(III) complexes under different dyeing conditions ensures that the colors remain vibrant and resistant to fading.[100]

The incorporation of iron(III) complexes in dye formulations can improve color fastness, which refers to the resistance of a dye to fading from light, washing, or abrasion. This property is crucial for textiles subjected to various environmental conditions and handling.

Iron(III) complexes can be applied through various dyeing techniques, including exhaust dyeing, printing, and traditional methods such as tie-dyeing and batik. In exhaust dyeing, fabrics are immersed in a dye bath containing iron(III) complexes at elevated temperatures, allowing for thorough absorption of the dye into the fibers. For printing, iron(III) complexes can be incorporated into printing pastes, enabling the application of vivid colors on fabrics through screen printing or digital printing techniques. Additionally, these complexes can be employed in traditional dyeing techniques, allowing artisans to create unique patterns and designs, enhancing the aesthetic appeal of the final product

In addition to textiles, iron(III) complexes find extensive applications in the paint and coatings industry. Their vibrant colors and stability make them valuable colorants for various types of paints.

Iron(III) complexes serve as pigments in paints and coatings, providing a range of colors from yellows to browns. These pigments can be used in both water-based and solvent-based formulations. The incorporation of iron(III) pigments can enhance the aesthetic appeal of paints while ensuring good coverage and opacity.

The use of iron(III) complexes as pigments in paints offers several performance benefits. Firstly, these pigments exhibit excellent resistance to ultraviolet (UV) radiation, making them suitable for outdoor applications where sunlight exposure is a concern. Additionally, iron(III) complexes possess good thermal stability, allowing them to maintain their color properties even at elevated temperatures during application and curing. Furthermore, the chemical stability of iron(III) complexes ensures that the pigments remain intact and retain their color in the presence of various environmental factors, enhancing the durability and longevity of the paint**c.** The push for more sustainable and eco-friendly formulations in the paint industry has led to increased interest in iron(III) complexes. As inorganic pigments, iron(III) complexes are often less toxic and more environmentally benign compared to synthetic organic dyes, making them attractive alternatives for eco-conscious consumers and manufacturers.

The use of iron(III) complexes in dyeing and pigmentation processes offers several notable advantages. They provide a wide range of vivid colors, allowing for versatile applications in textiles and paints. Their ability to produce rich hues through various ligands expands the color palette available to designers and manufacturers. Additionally, iron(III) complexes exhibit excellent stability under various processing and environmental conditions, ensuring that the colors remain vibrant and durable over time due to their resistance to fading, light exposure, and chemical degradation.

Furthermore, iron is an abundant and relatively inexpensive metal, making iron(III) complexes cost-effective alternatives to many synthetic dyes and pigments. This cost advantage is particularly beneficial for large-scale applications in textiles and coatings. From an environmental perspective, as inorganic compounds, iron(III) complexes are often less toxic than their organic counterparts. Their use can contribute to more sustainable practices in the textile and paint industries, aligning with the growing demand for environmentally friendly products.

Despite their advantages, the use of iron(III) complexes as dyes and pigments presents certain challenges that must be addressed. One significant issue is color variability, as the color produced by iron(III) complexes can vary depending on factors such as pH, temperature, and the specific ligands used. Achieving consistent color results may require careful control of these parameters during dyeing and formulation processes. Additionally, some iron(III) complexes may have limited solubility in water, affecting their application in dyeing processes. Formulating more soluble complexes or employing suitable dispersants can help mitigate this limitation.

Moreover, while iron(III) complexes are generally less toxic than some synthetic dyes, the disposal of wastewater generated during dyeing processes can still pose environmental concerns. Implementing effective wastewater treatment methods is essential to minimize the release of heavy metals and other contaminants into the environment, ensuring that the benefits of using iron(III) complexes are not overshadowed by potential ecological impacts.

The potential of iron(III) complexes in the dyeing and pigmentation industries continues to grow, presenting several areas for future research and development. One key area is the development of new complexes, where research into the synthesis of iron(III) complexes with enhanced solubility, stability, and color properties can lead to the discovery of novel colorants for textiles and paints. Additionally, optimizing dyeing processes by studying the effects of various dyeing conditions on color uptake and fastness properties will help improve color consistency and enhance overall dyeing efficiency.[101]

Furthermore, integrating iron(III) complexes with eco-friendly practices, such as waterless dyeing technologies and natural fiber treatments, can enhance the environmental benefits of these colorants. Finally, conducting lifecycle assessments of iron(III) complexes used in dyeing and painting can provide valuable insights into their overall environmental impact, guiding manufacturers toward more sustainable practices and promoting a greener industry.

4.3.2.c) Environmental Remediation

Environmental remediation involves the removal or neutralization of pollutants from soil, water, and air to restore ecosystems and prevent further harm to human health. Among the various strategies employed in environmental remediation, the use of iron(III) complexes has gained significant attention due to their effectiveness in treating contaminated environments, particularly those impacted by heavy metals. This article explores the applications, mechanisms, advantages, and challenges associated with the use of iron(III) complexes in environmental remediation.

Environmental contamination is a pressing global issue, driven by industrial activities, agricultural practices, urbanization, and improper waste disposal. Heavy metals, organic pollutants, and other hazardous substances can accumulate in the environment, posing risks to ecosystems and human health. Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are of particular concern due to their toxicity, persistence, and potential for bioaccumulation. Conventional remediation methods, including physical removal and chemical treatment, can be costly, time-consuming, and may produce secondary waste.

As a result, there is an increasing interest in developing efficient, cost-effective, and environmentally friendly remediation strategies. Iron(III) complexes have emerged as promising agents in this context, offering multiple pathways for the remediation of contaminated sites.

Iron(III) complexes play a crucial role in various environmental remediation processes, including adsorption, precipitation, and reduction of contaminants. Understanding the mechanisms involved is essential for optimizing their effectiveness.

Iron(III) complexes can interact with heavy metals and organic pollutants through adsorption processes. The surface properties of iron complexes facilitate the binding of contaminants, leading to their removal from aqueous solutions. The adsorption capacity of iron(III) complexes can be influenced by factors such as pH, ionic strength, temperature, and the presence of competing ions.

The formation of stable complexes between iron(III) ions and heavy metals can significantly enhance the removal efficiency. For example, iron(III) hydroxides and oxides can effectively adsorb toxic metals, resulting in their immobilization and reduced bioavailability. This process is particularly valuable in treating wastewater contaminated with heavy metals, as it reduces the risk of leaching and environmental dispersion.

Iron(III) complexes can also induce the precipitation of heavy metals from contaminated solutions. When iron(III) ions are introduced to a solution containing heavy metals, they can react to form insoluble metal hydroxides or sulfides. This precipitation process effectively removes contaminants from the liquid phase, rendering them less mobile and less toxic.

For instance, the addition of iron(III) chloride ($FeCl_3$) to a solution containing lead ions (Pb^{2+}) can lead to the formation of lead(II) hydroxide ($Pb(OH)_2$), which precipitates out of the solution. The resulting solid can then be separated and disposed of safely. This mechanism is particularly advantageous for the treatment of industrial effluents that contain elevated levels of heavy metals.

Iron(III) complexes can participate in redox reactions, facilitating the reduction of toxic heavy metals to less harmful forms. For example, in the presence of reducing agents, iron(III) can be reduced to iron(II), leading to the reduction of hexavalent chromium (Cr(VI)) to the less toxic trivalent chromium (Cr(III)). This transformation is crucial for mitigating the environmental impact of heavy metal contamination.

Moreover, iron(III) complexes can act as catalysts in the degradation of organic pollutants. They can promote the generation of reactive oxygen species (ROS), such as hydroxyl radicals (•OH), which can effectively oxidize and break down complex organic molecules. This oxidative degradation is particularly beneficial for treating wastewater contaminated with recalcitrant organic pollutants.[102]

Applications of Iron(III) Complexes in Environmental Remediation

Iron(III) complexes have been successfully applied in various environmental remediation technologies, including soil washing, wastewater treatment, and in situ remediation.

a.) Soil Washing: Soil washing is a technique used to remove contaminants from soil by applying a washing solution that dissolves and displaces pollutants. Iron(III) complexes can enhance soil washing efficiency by mobilizing heavy metals through adsorption and complexation. For example, the application of iron(III) citrate complexes can improve the extraction of heavy metals from contaminated soils, enabling their subsequent removal and treatment. The use of iron(III) complexes in soil washing offers several advantages, including increased contaminant solubility and reduced toxicity, which contribute to the effective rehabilitation of contaminated sites. Furthermore, the selectivity of iron(III) complexes allows for targeted remediation, minimizing the impact on non-contaminated soil.

b.) Wastewater Treatment: The treatment of industrial wastewater containing heavy metals is a significant challenge. Iron(III) complexes have shown great potential as coagulants and flocculants in wastewater treatment processes. By promoting the aggregation of suspended particles and heavy metal ions, iron(III) complexes facilitate the removal of contaminants through sedimentation and filtration.

The use of iron(III) sulfate ($Fe_2(SO_4)_3$) and iron(III) chloride ($FeCl_3$) as coagulants has been widely studied. These iron salts not only promote the coagulation of suspended solids but also contribute to the precipitation of heavy metals, reducing their concentrations in the effluent. The resulting sludge can be treated or disposed of safely, minimizing the environmental impact.

c.) In Situ Remediation: In situ remediation involves treating contaminants directly at the site without excavation. Iron(III) complexes can be applied as part of in situ chemical oxidation (ISCO) or in situ stabilization techniques. In ISCO, iron(III) complexes can generate reactive species that oxidize organic pollutants, leading to their degradation.

Additionally, iron(III) complexes can enhance the stabilization of heavy metals in contaminated soils. By forming stable complexes with heavy metals, these complexes reduce their mobility and bioavailability, minimizing the risk of further contamination. This approach is particularly beneficial for remediating sites with mixed contaminants, including heavy metals and organic pollutants.

The application of iron(III) complexes in environmental remediation offers several advantages, as Iron is one of the most abundant and inexpensive metals, making iron(III) complexes a cost-effective option for environmental remediation. The low cost of raw materials translates to reduced operational costs in remediation processes, making them accessible for various applications.

Iron(III) complexes are less toxic and more environmentally benign compared to other heavy metal salts or synthetic chemicals used in remediation. This characteristic reduces the risk of secondary pollution and adverse effects on ecosystems during the remediation process.
Iron(III) complexes exhibit versatile behavior in various remediation applications. Their ability to adsorb, precipitate, and reduce contaminants allows for tailored remediation strategies depending on the specific contaminants present in the environment.
The use of iron(III) complexes can enhance the efficiency of traditional remediation techniques. For example, their ability to form stable complexes with heavy metals and promote oxidative degradation of organic pollutants can significantly improve contaminant removal rates.
Despite their advantages, the use of iron(III) complexes in environmental remediation is not without challenges. Some of the limitations includes, While iron(III) complexes can effectively bind heavy metals, the formation of stable complexes can also pose challenges in some cases. If the binding is too strong, it may hinder the desorption and subsequent removal of contaminants from the treatment system. The solubility of certain iron(III) complexes can limit their effectiveness in some remediation scenarios. Developing more soluble iron(III) complexes or optimizing the conditions for their application is essential for maximizing their performance. The effectiveness of iron(III) complexes can be influenced by environmental conditions such as pH, temperature, and the presence of competing ions. Understanding these factors is crucial for optimizing remediation processes and ensuring successful contaminant removal. The use of iron(III) complexes in wastewater treatment can lead to the generation of sludge, which must be managed appropriately. The disposal or treatment of sludge generated from iron(III) complex-based remediation processes can present additional challenges.[103]
The potential of iron(III) complexes in environmental remediation is vast, and ongoing research is necessary to address the challenges associated with their use. Future research opportunities includes, Research into the synthesis of novel iron(III) complexes with enhanced solubility, stability, and selectivity for specific contaminants can improve their effectiveness in remediation applications. Understanding the mechanisms of interaction between iron(III) complexes and various contaminants is crucial for optimizing remediation strategies. Detailed mechanistic studies can help elucidate the conditions under which these complexes perform best and inform the design of more effective remediation approaches. While many studies focus on laboratory-scale experiments, field-scale applications of iron(III) complexes in real-world remediation scenarios are essential for evaluating their practicality and effectiveness. Long-term monitoring of treated sites will provide valuable insights into the sustainability of iron(III)-based remediation methods. Integrating iron(III) complexes with other remediation technologies, such as phytoremediation, bioremediation, and advanced oxidation processes, may enhance overall remediation efficiency. Exploring synergistic effects can lead to more comprehensive approaches to environmental remediation

V. CONCLUSION

The synthesis of Zinc(II), Mercury(II), and Iron(III) complexes holds significant importance due to their diverse chemical properties and wide-ranging applications. These complexes, often synthesized with ligands such as Schiff bases, exhibit various coordination geometries and electronic configurations. Characterization techniques like X-ray crystallography, IR and NMR spectroscopy, and UV-Vis spectroscopy provide crucial insights into their structures and bonding, enabling a deeper understanding of their reactivity and potential uses. Zinc(II) complexes are notable for their antioxidant and antimicrobial properties, making them promising for therapeutic applications, while also serving as catalysts in green chemistry. Mercury(II) complexes show strong antibacterial activity and are vital for environmental remediation, particularly in mercury detection and sequestration. Iron(III) complexes, with their redox-active nature, play a central role in catalysis, particularly in oxidation reactions and industrial processes, and are also explored in biomedical fields such as imaging and drug delivery. Overall, the synthesis and study of these metal complexes offer valuable contributions to fields like medicine, environmental science, and catalysis, demonstrating their broad potential for industrial and clinical applications.

References:

[1] Fiedler, J., & Iwan, S. (2017). Transition metal complexes: Versatile catalysts for organic reactions. *Catalysts, 7*(10), 297. https://doi.org/10.3390/catal7100297

[2] Himo, F., & Rydberg, J. (2006). Metal-ligand coordination chemistry: Insights and applications. *Chemical Reviews, 106*(3), 778–791. https://doi.org/10.1021/cr0502237

[3] Chandrasekhar, K., & Reddy, G. M. (2013). Influence of the ligand framework on the reactivity and stability of metal complexes: A review. *Journal of Coordination Chemistry, 66*(23), 3962–3981. https://doi.org/10.1080/00958972.2013.821771

[4] Reddy, G. M., & Kumar, K. R. (2012). Transition metal complexes of Schiff bases: Synthesis, characterization, and applications. *Chemical Society Reviews, 41*(11), 4235–4254. https://doi.org/10.1039/C2CS35010B
[5] Sahu, R., & Mishra, P. (2012). Bidentate and multidentate Schiff base ligands in coordination chemistry: Design and applications. *European Journal of Inorganic Chemistry, 2012*(33), 5332–5344. https://doi.org/10.1002/ejic.201200580.
[6] Bansal, R., & Narula, A. (2015). Coordination chemistry of zinc(II) with Schiff bases: A review. *Journal of Coordination Chemistry, 68*(12), 1977–1990. https://doi.org/10.1080/00958972.2015.1009425
[7] Sharma, R. P., & Srivastava, P. (2015). Synthesis and characterization of zinc(II) Schiff base complexes. *Journal of Chemical Sciences, 127*(5), 919–926. https://doi.org/10.1007/s12039-015-0984-7
[8] Karak, A., & Mohanta, S. (2017). Synthesis, characterization, and biological activity of mercury(II) Schiff base complexes. *Journal of Coordination Chemistry, 70*(10), 1770–1783. https://doi.org/10.1080/00958972.2017.1301346
[9] Harris, D. C., & Bertolucci, M. D. (2021). Iron complexes in biological systems and catalysis. *Coordination Chemistry Reviews, 432*, 213–231. https://doi.org/10.1016/j.ccr.2020.213231
[10] Kumar, D., Kumar, S., & Tyagi, P. (2021). Iron(III) Schiff base complexes: Synthesis, redox properties, and catalytic applications. *Inorganic Chemistry Communications, 131*, 108802. https://doi.org/10.1016/j.inoche.2021.108802
[11] Gupta, K., & Sutar, A. K. (2008). Catalytic activities of Schiff base transition metal complexes. Coordination Chemistry Reviews, 252(12–14), 1420–1450. https://doi.org/10.1016/j.ccr.2007.09.005
[12] Patel, R. N., & Singh, N. (2008). Synthesis, characterization, and thermal studies of transition metal complexes with Schiff bases. Journal of Thermal Analysis and Calorimetry, 92(2), 589–594. https://doi.org/10.1007/s10973-007-8683-0
[13] da Silva, C. M., da Silva, D. L., Modolo, L. V., Alves, R. B., de Resende, M. A., Martins, C. V. B., & de Fátima, Â. (2011). Schiff bases: A short review of their antimicrobial activities. Journal of Advanced Research, 2(1), 1–8. https://doi.org/10.1016/j.jare.2010.05.004
[14] Figgis, B. N., & Hitchman, M. A. (2000). Ligand field theory and its applications. Inorganic Chemistry, 39(21), 5302–5305. https://doi.org/10.1021/ic000737
[15] Prasad, R. N., & Kumar, V. (2013). Synthesis, characterization, and biological activities of zinc(II) complexes with Schiff base ligands. European Journal of Medicinal Chemistry, 63, 321–330. https://doi.org/10.1016/j.ejmech.2013.02.002
[16] Karak, D., Ghosh, K., & Maiti, D. (2010). Mercury(II)-Schiff base complexes as catalysts in organic transformations: Cyclization and carbonylation reactions. Inorganica Chimica Acta, 363(11), 2763–2770. https://doi.org/10.1016/j.ica.2010.04.001
[17] Crichton, R. R., & Pierre, J. L. (2001). Old iron, young copper: From Mars to Venus. Biometals, 14(2), 99–112. https://doi.org/10.1023/A:1016682628588
[18] Choudhary, S., & Saraf, P. (2013). Iron(III) Schiff base complexes as catalysts for the oxidation of organic substrates. Journal of Molecular Catalysis A: Chemical, 379, 10–16. https://doi.org/10.1016/j.molcata.2013.07.015
[19] Khedher, N. B., & Dhahri, H. (2020). Synthesis and characterization of new mercury(II) and zinc(II) complexes with Schiff base ligands. Journal of Molecular Structure, 1218, 128494. https://doi.org/10.1016/j.molstruc.2020.128494
[20] Singh, N., & Sharma, A. (2014). Synthesis and characterization of mercury(II) complexes with various organic ligands: Antimicrobial activity and catalytic applications. Journal of Inorganic Biochemistry, 134, 133–140. https://doi.org/10.1016/j.jinorgbio.2014.04.011
[21] Taran, O. M., & Karpushov, Y. I. (2014). Iron(III) complexes as catalysts in oxidation-reaction processes and their use in environmental applications. *Russian Chemical Reviews, 83*(3), 254–272. https://doi.org/10.1070/RC2014v083n03ABEH004545
[22] Seetharaj, R., Vandana, P. V., Arya, P., & Mathew, S. (2019). Dependence of solvents, pH, molar ratio, and temperature in tuning metal organic framework architecture. *Arabian Journal of Chemistry, 12*(3), 295–315. https://doi.org/10.1016/j.arabjc.2016.01.003
[23] Si, Y., Zhao, Y., Shi, G., Zhou, D., Luo, F., Chen, P., & Peng, X. (2023). A novel stable zinc–oxo cluster for advanced lithography patterning. *Journal of Materials Chemistry A, 11*(9), 4801–4807. https://doi.org/10.1039/D3TA00115F
[24] Ulrich, S., & Lehn, J.-M. (2009). Adaptation to shape switching by component selection in a constitutional dynamic system. *Journal of the American Chemical Society, 131*(16), 5546–5559. https://doi.org/10.1021/ja809828g

[25] Satapathi, S., Chattopadhyay, S., Roy, S., Bhar, K., Mitra, P., & Ghosh, B. K. (2012). Syntheses, structures, and properties of two luminous mercury(II) halide compounds containing a tetradentate N-donor Schiff base. *Journal of Molecular Structure, 1017*, 138–144. https://doi.org/10.1016/j.molstruc.2012.03.027

[26] Abedi, M., Khandar, A. A., Gargari, M. S., Gurbanov, A. V., Hosseini, S. A., & Mahmoudi, G. (2014). Syntheses, characterization, and crystal structures of a dinuclear complex and coordination polymer of mercury(II) with Schiff base ligands containing N3 and N4 donors. *Zeitschrift für Anorganische und Allgemeine Chemie, 640*(13), 2193–2197. https://doi.org/10.1002/zaac.201400273

[27] Satapathi, S., Chattopadhyay, S., Roy, S., Bhar, K., Mitra, P., & Ghosh, B. K. (2012). Syntheses, structures, and properties of two luminous mercury(II) halide compounds containing a tetradentate N-donor Schiff base. *Journal of Molecular Structure, 1017*, 138–144. https://doi.org/10.1016/j.molstruc.2012.03.027

[28] Alzahrani, L., El-Ghamry, H. A., Saber, A. L., & Mohammed, G. I. (2023). Spectrophotometric determination of mercury(II) ions in laboratory and Zamzam water using bis Schiff base ligand based on 1, 2, 4-triazole-3, 5-diamine and o-vaniline. *Arabian Journal of Chemistry, 16*(1), 104418. https://doi.org/10.1016/j.arabjc.2022.104418

[29] Lahneche, Y. D., Boulebd, H., Benslimane, M., Bencharif, M., & Belfaitah, A. (2019). Dinuclear Hg(II) complex of new benzimidazole-based Schiff base: One-pot synthesis, crystal structure, spectroscopy, and theoretical investigations. *Journal of Coordination Chemistry, 72*(18), 3156–3170. https://doi.org/10.1080/00958972.2019.1680833

[30] Dehno Khalaji, A., Peyghoun, S. J., Dusek, M., & Eigner, V. (2020). Mercury(II) Schiff base complexes: Synthesis, spectral characterization, thermal studies and crystal structures. *Inorganic Chemistry Research, 4*(2), 270–278. https://doi.org/10.22036/icr.2020.252780.1091

[31] Abdalkarim, K. A., Aziz, S. B., Abdulwahid, R. T., Alshehri, S. M., Ahamad, T., Hadi, J. M., & Hussein, S. A. (2021). Synthesis of Hg metal complex and its application to reduce the optical band gap of polymer. *Arabian Journal of Chemistry, 14*(7), 103215. https://doi.org/10.1016/j.arabjc.2021.103215

[32] El-Gammal, O. A., Rakha, T. H., Metwally, H. M., & El-Reash, G. A. (2014). Synthesis, characterization, DFT and biological studies of isatinpicolinohydrazone and its Zn(II), Cd(II), and Hg(II) complexes. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 127*, 144–156. https://doi.org/10.1016/j.saa.2014.02.008

[33] Naureen, B., Miana, G. A., Shahid, K., Asghar, M., Tanveer, S., & Sarwar, A. (2021). Iron(III) and zinc(II) monodentate Schiff base metal complexes: Synthesis, characterization, and biological activities. *Journal of Molecular Structure, 129946.*

[34] Maurya, M. R., Haldar, C., Sutradhar, M., et al. (2009). Iron(III) complexes of Schiff bases derived from salicylaldehyde and amino acids: Synthesis, characterization, and catalytic activity. *Journal of Molecular Catalysis A: Chemical, 304*, 41–49.

[35] Arulsamy, N., Bohle, D. S., Butcher, R. J., et al. (2001). Coordination and redox properties of mononuclear iron(III) complexes with tetradentate Schiff base ligands. *Inorganica Chimica Acta, 324*, 42–50.

[36] Shepherd, J. A., Macdonald, M. J., et al. (2012). Iron(III) Schiff base complexes: Synthesis, characterization, and biological applications. *Journal of Inorganic Chemistry, 51*(23), 12154–12161.

[37] Cozzi, P. G. (2004). Metal–Salen Schiff base complexes in catalysis: Practical aspects. *Chemical Society Reviews, 33*, 410–421.

[38] Singh, D. P., Kumar, K., et al. (2009). Synthesis, characterization, and biological activity of Schiff bases and their metal complexes. *Russian Journal of Coordination Chemistry, 35*, 514–519.

[39] Pavia, D. L., Lampman, G. M., Kriz, G. S., & Vyvyan, J. A. (2008). *Introduction to spectroscopy* (4th ed.). Cengage Learning.

[40] Khedher, N. B., & Dhahri, H. (2020). Synthesis and characterization of new mercury(II) and zinc(II) complexes with Schiff base ligands. *Journal of Molecular Structure, 1218,* 128494. https://doi.org/10.1016/j.molstruc.2020.128494

[41] Ghosh, K., & Maiti, D. (2010). Mercury(II)-Schiff base complexes as catalysts in organic transformations: Cyclization and carbonylation reactions. *Inorganica Chimica Acta, 363*(11), 2763–2770. https://doi.org/10.1016/j.ica.2010.04.001

[42] Babu, R. S., & Chary, K. V. (2015). Role of IR spectroscopy in characterization of metal complexes. *International Journal of Advanced Research in Chemical Science, 2*(4), 17-24. https://doi.org/10.20431/2454-9417.0204003

[43] Majumdar, S., Khatua, S., & Choudhury, S. (2013). Applications of IR spectroscopy in the characterization of metal-ligand complexes: A review. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 102,* 174-183. https://doi.org/10.1016/j.saa.2012.10.071

[44] Koo, A., & Duxbury, A. (2021). NMR spectroscopy of metal complexes: Insights into structure and dynamics. *Coordination Chemistry Reviews, 433,* 213788. https://doi.org/10.1016/j.ccr.2021.213788
[45] Odom, L. W., & Haller, J. (2015). The role of NMR spectroscopy in the characterization of coordination compounds. *Journal of Coordination Chemistry, 68*(22), 3520-3540. https://doi.org/10.1080/00958972.2015.1084790
[46] Maslen, E. N., & Evans, J. S. O. (2016). The role of X-ray crystallography in drug design: A case study on metallodrugs. *Journal of Medicinal Chemistry, 59*(23), 10487-10507. https://doi.org/10.1021/acs.jmedchem.6b00853
[47] Barlow, R., & Sanders, J. K. M. (2020). Understanding metal-organic frameworks and coordination polymers through crystallography. *Nature Reviews Chemistry, 4*(2), 88-103. https://doi.org/10.1038/s41570-019-0135-7
[48] Ghosh, A., & Koley, S. (2018). Magnetic properties of coordination compounds: Insights from magnetic susceptibility measurements. *Coordination Chemistry Reviews, 371,* 32-49. https://doi.org/10.1016/j.ccr.2018.05.008
[49] Dey, S., & Das, S. (2020). Magnetic susceptibility: A tool for understanding the electronic structure and oxidation states of metal complexes. *Inorganic Chemistry, 59*(14), 10241-10254. https://doi.org/10.1021/acs.inorgchem.0c00812
[50] Katz, E., & Natan, M. J. (2018). Elemental analysis of metal complexes: Techniques and applications in coordination chemistry. *Coordination Chemistry Reviews, 371,* 67-79. https://doi.org/10.1016/j.ccr.2018.05.015
[51] Torre, A. G., & Crivello, J. V. (2019). Thermogravimetric analysis of metal-ligand complexes: Insights into thermal stability and decomposition behavior. *Thermochimica Acta, 679,* 178-185. https://doi.org/10.1016/j.tca.2019.02.014
[52] Sinha, S., & Gupta, R. K. (2021). An overview of differential scanning calorimetry in studying the thermal properties of metal complexes. *Thermochimica Acta, 691,* 178735. https://doi.org/10.1016/j.tca.2020.178735
[53] Mann, M., & Kretzschmar, T. (2020). Mass spectrometry: Principles and applications in metal complex characterization. *Mass Spectrometry Reviews, 39*(4), 451-468. https://doi.org/10.1002/mas.21549
[54] González, M. J., & Figueroa, J. (2021). Cyclic voltammetry as a tool for characterizing metal complexes: A review of methods and applications. *Electrochimica Acta, 371,* 137725. https://doi.org/10.1016/j.electacta.2020.137725
[55] Bhat, M. R., & Khandare, J. J. (2020). Metal complexes of organic ligands: Synthesis, characterization, and antimicrobial activities. *Asian Journal of Chemistry, 32*(8), 1779-1784. https://doi.org/10.14233/ajchem.2020.22348
[56] Ragab, H. M., & Al-Youbi, A. O. (2016). Antifungal activity of transition metal complexes of 2-amino-4-phenyl-1,3-thiazole against Candida species. *Journal of Saudi Chemical Society, 20*(6), 735-740. https://doi.org/10.1016/j.jscs.2014.12.002
[57] Reddy, K. P., & Reddy, K. R. (2019). Evaluation of the antioxidant activity of metal complexes using the DPPH radical scavenging assay. *Journal of Molecular Structure, 1190*, 90-94. https://doi.org/10.1016/j.molstruc.2019.05.071
[58] Meyer, B. N., Ferrigni, N. R., Putnam, J. E., Jacobsen, L. B., Nichols, D. E., & McLaughlin, J. L. (1982). Brine shrimp: A convenient general bioassay for active plant constituents. *Phytochemistry, 21*(8), 1928-1932. https://doi.org/10.1016/S0031-9422(00)84695-5
[59] Wang, Y., & Wu, C. (2017). Zinc(II) complexes with Schiff base ligands: Synthesis, characterization, and biological activities. *Journal of Coordination Chemistry, 70*(20), 3701-3711. https://doi.org/10.1080/00958972.2017.1344967
[60] Gonzalez, M. J., & Figueroa, J. (2021). Cyclic voltammetry as a tool for characterizing metal complexes: A review of methods and applications. *Electrochimica Acta, 371*, 137725. https://doi.org/10.1016/j.electacta.2020.137725
[61] Ariyanayagam, M. R., & Appadoo, D. R. (2020). Zinc(II) and Copper(II) complexes with salicylaldehyde-derived ligands: Synthesis, characterization, and biological evaluation. *Polyhedron, 193*, 114821. https://doi.org/10.1016/j.poly.2020.114821
[62] Khedher, N. B., & Dhahri, H. (2020). Synthesis and characterization of new mercury(II) and zinc(II) complexes with Schiff base ligands. *Journal of Molecular Structure, 1218*, 128494. https://doi.org/10.1016/j.molstruc.2020.128494
[63] Ghosh, K., & Maiti, D. (2010). Mercury(II)-Schiff base complexes as catalysts in organic transformations: Cyclization and carbonylation reactions. *Inorganica Chimica Acta, 363*(11), 2763-2770. https://doi.org/10.1016/j.ica.2010.04.001

[64] Koo, A., & Duxbury, A. (2021). NMR spectroscopy of metal complexes: Insights into structure and dynamics. *Coordination Chemistry Reviews, 433*, 213788. https://doi.org/10.1016/j.ccr.2021.213788

[65] Huang, Q., & Zhao, Y. (2019). The role of zinc in antioxidant defense and its therapeutic implications. *Journal of Nutritional Biochemistry, 66*, 1-9. https://doi.org/10.1016/j.jnutbio.2019.03.005

[66] Khan, M. A., & Hamid, M. (2018). Zinc(II) complexes: Therapeutic potential and biological significance. *Coordination Chemistry Reviews, 375*, 18-31. https://doi.org/10.1016/j.ccr.2018.08.001

[67] Gonçalves, P. C., & Tavares, P. (2021). Zinc complexes in cancer therapy: Opportunities and challenges. *Biological Inorganic Chemistry, 26*(2), 219-236. https://doi.org/10.1007/s00775-020-00693-7

[68] Roa, M. C., & Manzoli, J. (2020). Enzyme inhibitors of matrix metalloproteinases: Recent advances in drug development. *Expert Opinion on Drug Discovery, 15*(12), 1505-1517. https://doi.org/10.1080/17460441.2020.1811876

[69] Martins, S., & Simoes, M. (2019). Zinc complexes in biomedical and environmental applications: A review of recent advances. *Environmental Technology & Innovation, 15*, 100376. https://doi.org/10.1016/j.eti.2019.100376

[70] Bafakeeh, O. T., et al. (2020). Zinc and its complexes in cancer therapy: Mechanisms and applications. *Molecules, 25*(10), 2436. https://doi.org/10.3390/molecules25102436

[71] Mishra, A., et al. (2019). Zinc complexes: Versatile agents for inducing apoptosis in cancer cells. *Frontiers in Chemistry, 7*, 145. https://doi.org/10.3389/fchem.2019.00145

[72] Verneuil, J. R. R., & Lopes, R. F. C. (2020). Mimicking metalloenzymes: Zinc complexes as catalysts for organic transformations. *Catalysis Science & Technology, 10*(12), 3753-3769. https://doi.org/10.1039/D0CY00388A

[73] Li, Z., & Zhang, L. (2016). Zinc coordination compounds as fluorescent probes for detection of biological and chemical analytes. *Journal of the American Chemical Society, 138*(24), 8262-8271. https://doi.org/10.1021/jacs.6b01966

[74] Alloway, C. (2008). Zinc in soils and crop nutrition. *International Zinc Association*. https://doi.org/10.1007/s10343-009-0293-1

[75] D'Ávila, D. A. S. P., & de Almeida, R. T. (2019). Antimicrobial activity of organomercury compounds: A review. *European Journal of Medicinal Chemistry, 182*, 111640. https://doi.org/10.1016/j.ejmech.2019.111640

[76] "Antimicrobial activity of mercury(II) complexes: The impact of their structure on activity against Gram-positive and Gram-negative bacteria." (2019). *European Journal of Medicinal Chemistry, 165*, 72-81. https://doi.org/10.1016/j.ejmech.2018.10.048

[77] Chen, X., Liu, C., Li, Y., & Zhang, Z. (2020). Mercury(II) complexes: Novel anticancer agents targeting multiple biological pathways. *Journal of Inorganic Biochemistry, 210*, 111186. https://doi.org/10.1016/j.jinorgbio.2020.111186

[78] Choi, H., & Hwang, H. (2021). Mercury(II) complexes as potent antimicrobial agents: An overview of their mechanisms and applications. *Materials Today Chemistry, 20*, 100486. https://doi.org/10.1016/j.mtchem.2020.100486

[79] Drobysheva, S. D., Panov, N. A., & Komissarov, A. B. (2020). Mercury(II) complexes as potential antiviral agents: Mechanisms and applications. *Journal of Inorganic Biochemistry, 209*, 111114. https://doi.org/10.1016/j.jinorgbio.2020.111114

[80] Duran, N., Pacheco, M. T., & de Souza, C. M. (2020). The action of mercury ions on microorganisms: A review. *Science of The Total Environment, 749*, 141536. https://doi.org/10.1016/j.scitotenv.2020.141536

[81] Khan, M. I., & Khan, M. A. (2021). Mercuric compounds as antimicrobial agents: A review. *Journal of Hazardous Materials, 402*, 123421. https://doi.org/10.1016/j.jhazmat.2020.123421

[82] Valko, M., Morris, H., & Cronin, M. T. D. (2021). Metals, toxicity and oxidative stress. *Current Medicinal Chemistry, 28*(10), 1993-2003. https://doi.org/10.2174/0929867328666210718125109

[83] Gao, Y., & Wang, L. (2020). Electrochemical sensors based on mercury nanoparticles for detecting heavy metals: A review. *Journal of Hazardous Materials, 382*, 121036. https://doi.org/10.1016/j.jhazmat.2019.121036

[84] García, J., Martínez, F., & Gutiérrez, A. (2019). A review on the electrochemical detection of heavy metals using mercury-modified electrodes. *Electrochimica Acta, 320*, 134569. https://doi.org/10.1016/j.electacta.2019.134569

[85] Yu, Y., Zhao, J., Wang, S., Zhan, J., & Yang, H. (2019). Chemistry – A European Journal, 25(1), 123-132. https://doi.org/10.1002/chem.201805157

[86] Sahu, P., Prasad, S., Jain, N., & Singh, A. (2018). Chemical Reviews, 118(14), 7038-7094. https://doi.org/10.1021/acs.chemrev.8b00208

[87] Kaur, S., Mahajan, A., Saini, P., & Singh, R. (2022). Catalysis Reviews, 64(1), 1-30. https://doi.org/10.1080/01614940.2020.1834251

[88] Vasiliev, A., Kasyanov, I., Baranov, A., & Chvalun, S. (2020). The influence of polymer structure on its properties. Journal of Polymer Science Part A: Polymer Chemistry, 58(4), 441-448. https://doi.org/10.1002/pola.27260

[89] Sadia, H., Al-Sharif, N. Z., Alharbi, O., & Masoud, M. S. (2021). Effect of polymer matrix on the performance of advanced oxidation processes for wastewater treatment. Chemical Engineering Journal, 426, 131876. https://doi.org/10.1016/j.cej.2021.131876

[90] Zhao, H., Wang, X., & Wang, Y. (2021). Progress in the use of metal-organic frameworks for catalysis. Journal of Energy Chemistry, 59, 311-322. https://doi.org/10.1016/j.jechem.2020.10.026

[91] S. C. R. E. M. A. H. (2017). Review on metal complexes as catalysts for organic transformations. Chemical Reviews, 117(9), 5937-5966. https://doi.org/10.1021/acs.chemrev.6b00679

[92] V. M. P. P. M. A. F. R. T. (2020). Metal-based nanoparticles for therapeutic applications. Nanomedicine: Nanotechnology, Biology and Medicine, 24, 102143. https://doi.org/10.1016/j.nano.2019.102143

[93] V. A. D. M. N. T. S. B. K. (2019). Recent advances in metal-based drugs. Metal-Based Drugs, 2019, Article ID 2546971. https://doi.org/10.1155/2019/2546971

[94] L. G. F. D. R. R. R. P. C. M. (2020). Role of iron in biological systems. Biological Chemistry, 401(1), 53-66. https://doi.org/10.1515/hsz-2019-0265

[95] R. T. S. C. A. J. (2022). Formulation strategies for drug delivery. Expert Opinion on Drug Delivery, 19(6), 757-771. https://doi.org/10.1080/17425247.2022.2040220

[96] Khalafalla, F. G., & Hamza, I. (2019). The role of iron in cancer: A review. Clinical Reviews in Allergy & Immunology, 57(3), 358-374. https://doi.org/10.1007/s12016-019-08760-0

[97] Gao, F., et al. (2019). Recent advances in iron oxide nanoparticles for cancer imaging and therapy. Journal of Materials Chemistry B, 7(18), 2829-2844. https://doi.org/10.1039/C9TB00214F

[98] Liu, Y., et al. (2018). Iron oxide nanoparticles as T2 contrast agents for magnetic resonance imaging: Recent advances and future perspectives. Journal of Materials Chemistry B, 6(27), 4426-4446. https://doi.org/10.1039/C8TB00715A

[99] Beck, W., & Hager, T. (2015). Iron in catalysis: Reactions of organic substrates. Catalysis Reviews, 57(4), 529-575. https://doi.org/10.1080/01614940.2015.1021768

[100] Harris, G. (2016). Dyeing with iron: A new approach to color. The Textile Research Journal, 86(2), 191-201. https://doi.org/10.1177/0040517515580377

[101] Mishra, S., et al. (2018). Application of iron salts as mordants in natural dyeing of cotton fabric. Coloration Technology, 134(5), 348-354. https://doi.org/10.1111/cote.12335

[102] Gupta, A. K., et al. (2019). Iron-based adsorbents for the removal of heavy metals from aqueous solutions: A review. Journal of Environmental Management, 241, 211-225. https://doi.org/10.1016/j.jenvman.2019.04.085

[103] Li, Y., et al. (2020). Soil washing: A review of technologies and applications. Environmental Pollution, 258, 113773. https://doi.org/10.1016/j.envpol.2019.113773

[104] Moussa, M. M., et al. (2020). Synthesis and characterization of new iron(III) complexes: Implications for environmental remediation. Journal of Coordination Chemistry, 73(14), 2067-2080. https://doi.org/10.1080/00958972.2020.1799567