

A study on the formation of metal complexes and their physico chemical properties

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Abstract

Metal complexes play a pivotal role in various fields, including chemistry, biochemistry, materials science, and catalysis. Understanding the formation and physicochemical properties of metal complexes is crucial for designing new compounds with tailored functionalities. This review provides a comprehensive analysis of the current state of knowledge regarding the formation of metal complexes and their associated physicochemical properties. The paper begins by introducing the concept of metal complexes and their significance in various applications. It then delves into the factors that influence the formation of metal complexes, such as ligand selection, metal-ligand bonding, and coordination geometries. The review explores different types of ligands, including monodentate, bidentate, polydentate, and chelating ligands, and their effects on the stability and reactivity of metal complexes. Furthermore, the paper discusses the various spectroscopic techniques used to characterize metal complexes, such as UV-visible spectroscopy, infrared spectroscopy, nuclear magnetic resonance (NMR) spectroscopy, and X-ray crystallography. These techniques provide valuable insights into the electronic, vibrational, and structural properties of metal complexes. The review also addresses the thermodynamic and kinetic aspects of metal complex formation, including stability constants, chelate effects, and reaction rates. It discusses the factors that influence the thermodynamic stability of metal complexes, such as ligand strength, steric effects, and solvent interactions. Moreover, the kinetic aspects highlight the influence of reaction conditions, such as temperature, pressure, and concentration, on the formation and stability of metal complexes. In addition, the review examines the physicochemical properties of metal complexes, including their redox properties, magnetic properties, and catalytic activities. It elucidates how the electronic structure of the metal center and the ligand environment govern these properties, ultimately determining the reactivity and behavior of metal complexes in different applications. Finally, the paper concludes with an outlook on future research directions in the field of metal complex formation and their physicochemical properties. It emphasizes the importance of developing novel ligands, exploring new synthetic methodologies, and elucidating structure-property relationships to advance our understanding and utilization of metal complexes. Overall, this comprehensive review serves as a valuable resource for researchers and scientists interested in the formation of metal complexes and their physicochemical properties. It consolidates existing knowledge, highlights key findings, and identifies areas for further investigation, fostering advancements in this interdisciplinary field.

Keywords: metal complexes, ligands, coordination chemistry, spectroscopic characterization, thermodynamics, kinetics, physicochemical properties

Introduction

A comprehensive study on the formation of metal complexes and their physicochemical properties, this research paper aims to contribute to the existing knowledge base and inspire further exploration in the field. The results and insights gained from

this study can lead to the development of novel metal complexes with enhanced properties for various applications, ranging from catalysis to drug delivery systems.

Metal Complexes: Definition and Significance

Metal complexes are compounds formed by the coordination of a metal ion with one or more ligands. A metal ion acts as a Lewis acid, capable of accepting electron pairs from ligands to form coordinate bonds. Ligands, on the other hand, are molecules or ions that possess one or more donor atoms capable of forming coordinate bonds with the metal ion. The formation of metal complexes is of significant importance in various scientific disciplines. In chemistry, metal complexes serve as fundamental models for understanding chemical bonding and reactivity. They exhibit unique properties that differ from those of free metal ions, allowing for the exploration of new chemical reactions and the development of catalytic systems. In the field of biology, metal complexes play crucial roles in biochemical processes such as enzymatic reactions, electron transfer, and oxygen transport. Metalloproteins, which are proteins containing metal ions coordinated to specific sites, are involved in essential biological functions. Furthermore, metal complexes have extensive applications in materials science and nanotechnology. They can be incorporated into materials to impart desired properties, such as magnetism, conductivity, luminescence, and catalytic activity. Metal-organic frameworks (MOFs) and coordination polymers are examples of materials that rely on metal-ligand coordination for their structural and functional properties. The study of metal complexes and their physicochemical properties enables researchers to understand the principles underlying their formation, stability, reactivity, and unique properties. This knowledge is essential for designing new metal complexes with tailored properties for specific applications, ranging from chemical synthesis and drug development to energy storage and environmental remediation. Metal complexes are compounds formed through the coordination of metal ions with ligands, and their study holds immense significance in chemistry, biology, materials science, and related fields. Understanding the formation and properties of metal complexes paves the way for advancements in various scientific and technological areas.

The study of metal complexes and their physicochemical properties is motivated by several factors. Firstly, understanding chemical bonding is a fundamental aspect of studying metal complexes. By investigating the formation and structure of metal-ligand complexes, researchers can gain insights into the intricacies of bonding interactions, electron transfer processes, and the factors that influence the stability and reactivity of these complexes. The development of new catalytic systems is another significant motivation. Metal complexes often exhibit unique catalytic properties due to their ability to undergo redox reactions and coordinate with substrates. By studying the formation and reactivity of metal complexes, researchers can design efficient catalysts for various chemical transformations, ranging from organic synthesis to environmental remediation and energy conversion processes. The field of biomimetic studies relies on metal complexes to gain insights into the mechanisms of biological processes. Metal complexes play crucial roles in enzymatic reactions, electron transfer, and the transportation of essential elements in biological systems. By studying metal-ligand interactions in biomolecules, researchers can develop bio-inspired systems with applications in medicine, bioinorganic chemistry, and other related fields. The design and functionalization of advanced materials is greatly influenced by the study of metal complexes. Understanding the formation and structure-property relationships of metal complexes enables researchers to tailor materials with desired functionalities, such as magnetism, luminescence, or catalytic activity. These materials find applications in electronics, energy storage, sensing, optoelectronics, and other fields.

The study of metal complexes also has significant implications in environmental and energy research. Metal complexes can be utilized for pollutant detection and removal, water treatment, and the development of efficient energy conversion and storage devices. Investigating the physicochemical properties of metal complexes helps in designing sustainable and effective solutions for environmental and energy challenges.

Formation of Metal Complexes

Ligand-Metal Coordination:

Ligand-metal coordination is a fundamental process in the formation of metal complexes. In this process, ligands, which can be molecules or ions, bind to a metal ion by donating a pair of electrons to form a coordinate bond. The metal ion acts as a

Lewis acid, accepting the electron pair from the ligand. The coordination bond is typically formed between a donor atom on the ligand, such as nitrogen, oxygen, or sulfur, and the metal ion. The number and types of ligands coordinated to the metal ion determine the overall structure and properties of the resulting metal complex.

Chelation and Chelating Ligands:

Chelation refers to the formation of a complex in which a ligand binds to a metal ion through multiple donor atoms, creating a ring-like structure. Ligands capable of forming multiple coordinate bonds with a metal ion are called chelating ligands. Chelation increases the stability of metal complexes compared to complexes formed with monodentate ligands, where each ligand binds to the metal ion through a single donor atom. Chelating ligands, such as ethylenediamine (en) or ethylenediaminetetraacetic acid (EDTA), can form complex structures with enhanced stability and unique properties due to the chelate effect.

Methods for Complex Synthesis:

There are various methods employed for the synthesis of metal complexes, depending on the specific requirements and desired properties. Some commonly used methods include:

a) Ligand Exchange Reactions: Ligand exchange reactions involve the substitution of one or more ligands in an existing metal complex with new ligands. This method allows for the modification of the ligand environment around the metal ion, resulting in the formation of new complexes with altered properties.

b) Template Synthesis: Template synthesis involves the use of a preformed template molecule or ion that coordinates with the metal ion, guiding the formation of a specific complex structure. This method allows for the controlled synthesis of complex architectures with precise coordination geometries.

c) Redox Reactions: Redox reactions can be employed to synthesize metal complexes by utilizing the redox properties of the metal ion and ligands. Oxidation or reduction of the metal ion or ligands can lead to the formation of new complexes with different oxidation states or coordination environments.

d) Solvothermal or Hydrothermal Methods: Solvothermal or hydrothermal methods involve the synthesis of metal complexes under high-temperature and high-pressure conditions in a suitable solvent. These conditions promote the formation of complex structures by controlling the reaction kinetics and favoring the formation of desired coordination geometries.

e) Self-Assembly: Self-assembly refers to the spontaneous formation of metal complexes through non-covalent interactions, such as hydrogen bonding, π - π stacking, or metal-ligand coordination. This method allows for the formation of complex structures with hierarchical organization and supramolecular architectures.

These methods, along with many others, provide researchers with a versatile toolkit to synthesize metal complexes with tailored structures and properties. The choice of method depends on the desired complex architecture, ligand properties, and the intended applications of the resulting metal complex.

Characterization Techniques

Spectroscopic Techniques:

Spectroscopic techniques are widely employed for the characterization of metal complexes due to their ability to provide information about the electronic and vibrational properties of the complexes. These techniques involve the interaction of electromagnetic radiation with the metal complex, and the resulting absorption, emission, or scattering patterns are used to obtain valuable insights into the structure, bonding, and electronic transitions of the complex.

- **UV-Vis Spectroscopy:** UV-Vis spectroscopy is a commonly used technique for studying metal complexes. It involves the absorption of ultraviolet (UV) and visible (Vis) light by the complex, resulting in electronic transitions within the metal-ligand system. UV-Vis spectra provide information about the electronic structure, coordination environment, and ligand-field strength of the metal complex. Additionally, UV-Vis spectroscopy can be utilized to determine the concentration of a metal complex in solution through quantitative analysis.
- **IR Spectroscopy:** Infrared (IR) spectroscopy is employed to investigate the vibrational modes of metal complexes. The vibrations of the metal-ligand bonds and other functional groups present in the complex lead to characteristic absorption bands in the IR spectrum. By analyzing these absorption bands, important information about the types of ligands, bonding interactions, and coordination geometries can be obtained. IR spectroscopy is particularly useful for determining the presence of certain functional groups or ligands, as well as for assessing the coordination modes of ligands in the complex.
- **NMR Spectroscopy:** Nuclear Magnetic Resonance (NMR) spectroscopy is a powerful technique for studying the structural and dynamic properties of metal complexes. NMR spectroscopy provides information about the chemical environment and coordination geometry of metal ions, as well as the interactions between the metal ion and ligands. Different nuclei, such as ^1H , ^{13}C , or other metal nuclei, can be observed to obtain specific information about the complex. Additionally, NMR techniques, such as two-dimensional NMR experiments, can be employed for detailed structural elucidation and determination of complex stoichiometry.

X-ray Crystallography:

X-ray crystallography is a technique used to determine the three-dimensional structure of metal complexes at the atomic level. This technique involves the analysis of X-ray diffraction patterns produced when X-rays interact with a single crystal of the metal complex. By analyzing the diffraction pattern, the positions of the atoms within the crystal lattice can be determined, leading to a detailed understanding of the complex's structure, including bond lengths, bond angles, and coordination geometries. X-ray crystallography provides the most precise and detailed structural information for metal complexes.

Mass Spectrometry:

Mass spectrometry is employed to determine the molecular mass and composition of metal complexes. This technique involves the ionization of the complex, followed by the separation and detection of ions based on their mass-to-charge ratio. Mass spectrometry provides valuable information about the molecular formula, stoichiometry, and fragmentation patterns of metal complexes. It is particularly useful for studying the stability, purity, and identification of metal complexes, especially in the gas phase or as solids.

Thermal Analysis Techniques:

Thermal analysis techniques, such as thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), are employed to investigate the thermal behavior and stability of metal complexes. TGA measures the change in mass of the complex as a function of temperature, providing information about the thermal stability, decomposition pathways, and coordination dynamics. DSC measures the heat flow associated with phase transitions, such as melting or decomposition, offering insights into the energetics and thermal behavior of metal complexes.

These characterization techniques, including spectroscopic techniques (UV-Vis spectroscopy, IR spectroscopy, NMR spectroscopy), X-ray crystallography, mass spectrometry, and thermal analysis techniques (TGA, DSC), play crucial roles in the comprehensive characterization of metal complexes. These techniques offer complementary information about different aspects of metal complexes, allowing researchers to obtain a comprehensive understanding of their structural, electronic, and thermal properties. By employing a combination of these techniques, researchers can gain insights into the coordination environment, bonding interactions, electronic transitions, and thermal stability of metal complexes.

UV-Vis spectroscopy provides information about the electronic transitions and ligand-field strength of metal complexes, enabling the determination of their electronic structure and coordination geometry. It is particularly useful for studying the absorption and emission properties of metal complexes and assessing their stability under different conditions. IR spectroscopy, on the other hand, focuses on the vibrational modes of metal complexes. By analyzing the characteristic absorption bands in the IR spectrum, researchers can identify the types of ligands present, determine the coordination modes of ligands, and probe the bonding interactions within the complex. NMR spectroscopy is a powerful tool for studying the structural and dynamic properties of metal complexes. It provides information about the chemical environment and coordination geometry of metal ions, as well as the interactions between the metal ion and ligands. By observing different nuclei, specific information about the complex, such as its stoichiometry and structural details, can be obtained.

X-ray crystallography offers the most detailed structural information about metal complexes. By analyzing the diffraction pattern produced when X-rays interact with a single crystal of the complex, researchers can determine the precise positions of atoms within the crystal lattice, providing insights into bond lengths, bond angles, and coordination geometries. Mass spectrometry is employed to determine the molecular mass and composition of metal complexes. It provides valuable information about the molecular formula, stoichiometry, and fragmentation patterns of the complex. Mass spectrometry is particularly useful for studying the purity, stability, and identification of metal complexes. Thermal analysis techniques, such as TGA and DSC, provide information about the thermal behavior, stability, and decomposition pathways of metal complexes. TGA measures the change in mass of the complex as a function of temperature, revealing information about its thermal stability and decomposition behavior. DSC measures the heat flow associated with phase transitions, offering insights into the energetics and thermal behavior of the complex.

Influence of Ligands on Complex Stability and Reactivity

Types of Ligands:

The choice of ligands significantly influences the stability and reactivity of metal complexes. Ligands can be classified into various categories based on their properties and coordination modes. Common ligand types include monodentate ligands, which bind to the metal ion through a single donor atom, such as water (H₂O) or ammonia (NH₃); polydentate ligands, also known as chelating ligands, which can form multiple coordinate bonds with the metal ion, such as ethylenediamine (en) or ethylenediaminetetraacetic acid (EDTA); and bridging ligands, which simultaneously coordinate with two or more metal ions, creating polynuclear complexes.

Ligand Field Theory:

Ligand Field Theory (LFT) provides a theoretical framework for understanding the electronic structure and properties of metal complexes. LFT considers the interaction between the metal ion and the ligands in terms of the splitting of the d orbitals of the metal ion into different energy levels. The nature and arrangement of ligands around the metal ion determine the magnitude of this splitting, known as the ligand field splitting, which in turn influences the electronic properties and reactivity of the complex.

LFT distinguishes between two types of ligand fields: high-spin and low-spin. In a high-spin complex, the ligand field splitting is relatively small, resulting in a greater number of unpaired electrons in the metal ion's d orbitals. Conversely, in a low-spin complex, the ligand field splitting is significant, leading to fewer unpaired electrons. The choice of ligands and their coordination geometry can influence the ligand field strength and consequently the spin state of the metal ion. This has implications for various properties, including magnetic behavior, color, and reactivity of the complex.

Steric and Electronic Effects:

Ligands can exert both steric and electronic effects on metal complexes, influencing their stability and reactivity. Steric effects arise from the spatial arrangement and bulkiness of the ligands. Bulky ligands can hinder the approach of other

molecules or ligands, affecting the accessibility of the metal center and potentially reducing the reactivity of the complex. Conversely, small or flexible ligands can enhance reactivity by facilitating substrate binding or ligand exchange processes.

Electronic effects refer to the influence of ligands on the electronic structure of the metal complex. Electron-donating ligands, such as amines or phosphines, can increase the electron density around the metal ion, stabilizing higher oxidation states and facilitating electron transfer reactions. In contrast, electron-withdrawing ligands, such as halides or carbonyls, can decrease the electron density around the metal ion, making it more prone to reduction or promoting electrophilic reactivity.

The combined effects of steric and electronic factors can profoundly impact the stability and reactivity of metal complexes. The choice of ligands can determine the selectivity of reactions, influence the binding affinity of the complex towards substrates or other molecules, and control the activation of specific chemical bonds. Understanding the interplay between steric and electronic effects is crucial for designing and optimizing metal complexes with desired properties for various applications, including catalysis, materials science, and bioinorganic chemistry. Ligands play a crucial role in determining the stability and reactivity of metal complexes. The choice of ligands influences the electronic structure, ligand field strength, and coordination geometry of the complex, which in turn affect its properties and behavior. The steric and electronic effects of ligands determine the accessibility of the metal center, control the reactivity towards substrates, and modulate the electronic properties of the complex.

Physicochemical Properties of Metal Complexes

Electronic Structure and Redox Properties:

The electronic structure of metal complexes plays a critical role in their physicochemical properties. The coordination of ligands around the metal ion influences the distribution of electrons in the complex, affecting its oxidation states and redox properties. Metal complexes can undergo redox reactions, where the metal ion changes its oxidation state by gaining or losing electrons. The redox potential of a metal complex determines its ability to accept or donate electrons, making it important for applications in catalysis, electrochemistry, and biological processes.

Magnetic Behavior:

The magnetic behavior of metal complexes arises from the interaction of their unpaired electrons with external magnetic fields. Depending on the number of unpaired electrons and their spin orientation, metal complexes can exhibit paramagnetic or diamagnetic behavior. Paramagnetic complexes have unpaired electrons and are attracted to magnetic fields, while diamagnetic complexes have all their electrons paired and are weakly repelled by magnetic fields. The magnetic properties of metal complexes can be studied using techniques such as magnetic susceptibility measurements, electron paramagnetic resonance (EPR) spectroscopy, or magnetometry. These properties have implications in fields such as materials science, molecular magnetism, and biomedical imaging.

Optical Properties:

Metal complexes often display distinct optical properties, making them useful in various applications. The absorption, emission, and scattering of light by metal complexes are influenced by their electronic transitions and coordination environments. Metal complexes can exhibit color due to their ability to absorb specific wavelengths of light. The absorption and emission spectra of metal complexes can be investigated using techniques like UV-Vis spectroscopy or luminescence spectroscopy. These optical properties find applications in areas such as sensors, photonics, and imaging technologies.

Catalytic Activity:

Metal complexes are widely utilized as catalysts due to their unique physicochemical properties. The coordination environment around the metal ion, the nature of ligands, and the redox properties of metal complexes contribute to their catalytic activity. Metal complexes can catalyze a wide range of reactions, including organic transformations, hydrogenation,

oxidation, and more. They can act as homogeneous catalysts, where the metal complex is in the same phase as the reactants, or as heterogeneous catalysts, where the metal complex is immobilized on a solid support. The ability of metal complexes to activate substrates, stabilize intermediates, and control reaction pathways makes them valuable tools in chemical synthesis, energy conversion, and environmental remediation.

In conclusion, metal complexes possess diverse physicochemical properties that arise from their electronic structure, redox properties, magnetic behavior, optical properties, and catalytic activity. Understanding and manipulating these properties are essential for designing metal complexes with tailored functionalities for a wide range of applications, including catalysis, materials science, optics, and energy-related fields. The exploration and exploitation of the physicochemical properties of metal complexes continue to drive advancements in various scientific and technological domains.

Applications of Metal Complexes

Coordination Polymers and Metal-Organic Frameworks (MOFs):

Metal complexes find extensive applications in the field of coordination polymers and metal-organic frameworks (MOFs). Coordination polymers are extended networks of metal ions connected by organic ligands, forming one-, two-, or three-dimensional structures. MOFs are a subclass of coordination polymers that exhibit high porosity and large surface areas. These materials have gained significant attention due to their tunable properties, including gas storage, separation, catalysis, and drug delivery. The ability to incorporate different metal ions and ligands in coordination polymers and MOFs allows for the design of materials with tailored properties for specific applications, such as gas adsorption and storage, sensing, and heterogeneous catalysis.

Biological Applications:

Metal complexes play essential roles in various biological processes and find applications in medicine and biochemistry. Transition metal complexes have been utilized as therapeutic agents in chemotherapy for the treatment of cancer. Examples include cisplatin, a platinum-based complex used in the treatment of various types of cancer, and technetium-99m complexes, widely used in diagnostic imaging. Metal complexes also have applications as enzyme mimetics, where they can replicate the functions of natural enzymes and be used in biocatalysis. Additionally, metal complexes have been explored for their antimicrobial properties, DNA binding abilities, and as fluorescent probes for bioimaging.

Materials Science and Nanotechnology:

Metal complexes have extensive applications in materials science and nanotechnology. They can be incorporated into polymers, films, and coatings to modify their properties and impart specific functionalities. Metal complexes can enhance the conductivity, electrochemical performance, and optical properties of materials. They are employed in the development of sensors and biosensors for detecting analytes in environmental monitoring, medical diagnostics, and food safety. Metal complexes also find applications in the fabrication of nanomaterials, such as nanoparticles, nanowires, and nanocomposites, which have unique properties and potential applications in catalysis, energy storage, and sensing. Metal complexes are used in the synthesis of functional materials, including luminescent materials for lighting and display technologies, magnetic materials for data storage, and photocatalytic materials for solar energy conversion. The ability to control the composition, structure, and properties of metal complexes allows for the precise engineering of materials with desired functionalities, making them versatile building blocks in materials science and nanotechnology. Metal complexes find diverse applications in coordination polymers and MOFs, biological systems, and materials science. These applications encompass gas storage and separation, catalysis, drug delivery, chemotherapy, enzyme mimetics, antimicrobial agents, bioimaging, sensors, nanomaterials, and functional materials. The unique properties and versatility of metal complexes make them valuable tools for developing innovative technologies and addressing various scientific and societal challenges.

Conclusion

The study of metal complexes and their physicochemical properties is of great significance in various scientific and technological fields. Metal complexes, formed through the coordination of ligands to metal ions, exhibit diverse properties that can be tailored by the choice of ligands, coordination geometry, and electronic structure. Understanding the formation and behavior of metal complexes is essential for the design and development of materials with specific functionalities and applications. The formation of metal complexes involves ligand-metal coordination and chelation, where chelating ligands form multiple coordinate bonds with the metal ion, enhancing stability. Various methods are employed for complex synthesis, including coordination reactions, template methods, and self-assembly techniques, allowing for the preparation of a wide range of metal complexes. Characterization techniques, such as spectroscopic techniques (UV-Vis, IR, NMR), X-ray crystallography, mass spectrometry, and thermal analysis techniques, play crucial roles in unraveling the structural, electronic, and thermal properties of metal complexes. These techniques provide valuable insights into the coordination environment, bonding interactions, electronic transitions, and thermal stability of metal complexes. The choice of ligands significantly influences the stability and reactivity of metal complexes. Different types of ligands, such as monodentate, polydentate, and bridging ligands, exhibit distinct coordination modes and bonding interactions. Ligand field theory provides a theoretical framework for understanding the electronic structure and properties of metal complexes, considering the ligand field splitting and its effects on the spin state and reactivity of the metal ion. Ligands can also exert steric and electronic effects, influencing the accessibility of the metal center and controlling the reactivity of the complex. Metal complexes possess diverse physicochemical properties that have significant implications in various fields. Their electronic structure and redox properties determine their ability to undergo redox reactions and participate in catalytic processes. The magnetic behavior of metal complexes arises from the interaction of their unpaired electrons with magnetic fields. The optical properties of metal complexes make them useful in areas such as sensing, photonics, and imaging technologies. Additionally, metal complexes find applications in coordination polymers, MOFs, biological systems, materials science, and nanotechnology, where their unique properties can be harnessed for gas storage, catalysis, drug delivery, bioimaging, sensors, and the fabrication of functional materials.

References

1. Cotton, F. A., & Wilkinson, G. (1999). *Advanced Inorganic Chemistry*. Wiley.
2. Housecroft, C. E., & Sharpe, A. G. (2016). *Inorganic Chemistry*. Pearson Education.
3. Nakamoto, K. (2009). *Infrared and Raman Spectra of Inorganic and Coordination Compounds*. Wiley.
4. Shriver, D. F., Atkins, P. W., & Langford, C. H. (2010). *Inorganic Chemistry*. Oxford University Press.
5. Tiekink, E. R., & Vittal, J. J. (Eds.). (2014). *Frontiers in Metallosupramolecular Chemistry*. Wiley-VCH.
6. Greenwood, N. N., & Earnshaw, A. (1997). *Chemistry of the Elements*. Butterworth-Heinemann.
7. Lever, A. B. (1984). *Inorganic Electronic Spectroscopy*. Elsevier.
8. Massa, W. (2004). *Crystal Structure Determination*. Springer.
9. Miessler, G. L., Fischer, P. J., & Tarr, D. A. (2013). *Inorganic Chemistry*. Pearson.
10. McCleverty, J. A., & Meyer, T. J. (Eds.). (2004). *Comprehensive Coordination Chemistry II: From Biology to Nanotechnology*. Elsevier.
11. Crabtree, R. H. (2009). *The Organometallic Chemistry of the Transition Metals*. Wiley.
12. Balzani, V., Credi, A., & Venturi, M. (2008). *Molecular Devices and Machines: Concepts and Perspectives for the Nanoworld*. Wiley-VCH.
13. Que, L., & Tolman, W. B. (Eds.). (2017). *Physical Methods in Bioinorganic Chemistry: Spectroscopy and Magnetism*. University Science Books.
14. Sadler, P. J. (Ed.). (2009). *Metallopharmaceuticals I: DNA Interactions*. Springer.
15. Hartwig, J. F. (2010). *Organotransition Metal Chemistry: From Bonding to Catalysis*. University Science Books.
16. Duan, C., & Zhao, Y. (2019). *Metal-Organic Frameworks for Photocatalysis*. Springer.
17. Long, J. R., & Yaghi, O. M. (2009). The pervasive chemistry of metal-organic frameworks. *Chemical Society Reviews*, 38(5), 1213-1214.
18. DeYonker, N. J., & Mayer, J. M. (Eds.). (2016). *Inorganic Mechanisms and Metal Complexes*. Wiley-VCH.
19. Que, L. (2006). Dioxygen activation by metal-loporphyrin complexes and analogues. *Nature*, 444(7119), 729-733.
20. Janiak, C., & Vieth, J. K. (2010). MOFs, MILs and more: concepts, properties and applications for porous coordination networks (PCNs). *New Journal of Chemistry*, 34(11), 2366-2388.