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Zinc (II) Ternary Complexes: A Comprehensive Review

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Abstract: Complexes of Zinc (II) are synthesized by the coordination of zinc ions with primordial and supplementary ligands and have shown potential to be used in numerous fields including catalysis, material science and biomedical. In this review, the solutions synthesis and electrodeposition methods have been discussed in detail where the choice of ligand has been shown as the key to the desired morphology and properties of the Mn oxide. The geometry, stability, and electronic properties of these complexes are further described by spectroscopy, X-ray diffraction, and thermal studies. Emphasized are their optical, electronic, and biological performances which confirm their versatility in organic catalysis, drug delivery and sensing systems. Some limitations and future development are discussed concerning the need to improve selectivity, increase the yield of synthesis in an industrial point of view, and the use of more green protocols. This surveying paper will to some extent, shed light on the growth area that relates to Zinc (II) ternary complexes and their versatility.

***Index Terms* - zinc ion, catalysis, material science, biomedical, ligand, spectroscopy, X-ray diffraction, thermal studies, green protocols.**

I. INTRODUCTION

Zinc (II) can be found in biological systems being a micro-component of many enzymes that control important metabolic and biochemical processes. This has made the complexes of zinc as crucial center of research in medicinal chemistry due to its capacity to bind with different ligands. Although there is ample information about binary zinc complexes, ternary zinc complexes, where zinc is coordinated with two different types of ligands, has been much less investigated. Such complexes are structurally diverse and functionally flexible and show increased stability and catalytic activity, thus offering potential for novel therapeutic targeting and industrial uses.

Ternary complexes based on zinc have attracted considerable interest in the contexts of catalysis, biology, material science and environmental chemistry, due to their convenient synthesis, low toxicity, and environmentally benign character. By virtue of their distinctive physical and chemical properties, arising from the intimate structural and electronic interactions operative in these systems, these supramolecular assemblies are essential for sustainable chemistry and biomedical research. The purpose of this study is to synthesize and characterize zinc (II) ternary complexes using Schiff base ligands and biologically active molecules, vitamins, antibiotics and amino acids. This research explores new structural insights and applications of zinc (II) complexes through potentiometric analysis of stability constants aimed to discover new structural and functional applications of zinc (II) complexes across the spectrum of multidisciplinary fields.

2. Synthesis

2.1 Ligand Selection

The selection of zinc (II) ligands is critical in defining some of the properties of the ternary complexes.

The ligands are categorized into:

• **Primary ligands**: Nitrogen or oxygen donors, like amines, imidazole and phenolates, are commonly found and strongly bind to the zinc center.

• **Secondary ligands**: The complex is typically accompanied by auxiliary molecules, such as carboxylates, phosphonates or aromatic heterocycles, which improve the structural stability and functionality of the complex.

2.2 Synthetic Methods

- **Direct Reaction:** This is a straightforward technique involving reactions of zinc salts (e.g., $ZnCl_2$, $ZnSO_4$) with ligands in appropriate solvents: water, ethanol or acetonitrile. The composition of the product is controlled by adjustments of solvent polarity and reaction conditions.
- **Solvothermal/Hydrothermal\\Synthesis:** Crystallinity and purity are improved under high temperature and high pressure conditions. This method is also suitable for making complexes with unique architectures.
- **Template-Assisted Synthesis:** Zinc complexes are assembled by means of assembly to preformed ligand frameworks to lead to precise control over the final product's geometry and properties.
- **In Situ Reactions:** Diversity of the resulting complexes is achieved by virtue of generating ligands in the reaction medium.

2.3 Optimization of Reaction Parameters

The stoichiometry and coordination geometry are systematically optimized as functions of temperature, pH, reaction time, and ligand-to-metal ratios. Also, the crystallization process and the solubility of complexes depend on these parameters.

3. Characterization Techniques

3.1 Spectroscopic Methods

- **UV-Vis Spectroscopy**: It provides insight into electronic transitions, and ligand-metal charge transfer, which is critically important to optical properties.
- **FT-IR Spectroscopy:** Functional groups and intermetallic ligand interactions are identified and monitored through characteristic vibrational bands.
- **NMR Spectroscopy:** It probes the chemical environment of ligands, and in doing so reveals that information about the complex's symmetry and dynamics.3.2 Structural Characterization.
- **X-Ray Crystallography:** Providing exact 3D structural details of coordination numbers and geometries such as tetrahedral, square planar, or octahedral.

3.3 Thermal and Electrochemical Analyses

- **Thermal Analysis (TGA/DSC):** Assesses thermal stability and decomposition patterns, crucial for determining practical applicability.
- **Electrochemical Studies:** Evaluate redox properties and complex stability, which are critical for catalytic and electronic applications.

3.4 Microscopic Techniques

- **SEM/TEM:** Examine the morphology and particle size of zinc complexes, especially when used in materials science applications.

4. Physical Properties

4.1 Structural Diversity

Flexible coordination geometries of zinc (II) complexes make them able to adapt to different ligand framework environments and structures vary from mononuclear to polynuclear and from metal organic frameworks (MOFs).

4.2 Optical Properties

- Zinc (II) complexes often exhibit fluorescence, making them promising candidates for photonic and luminescent materials.
- Ligand-to-metal charge transfer transitions contribute to their distinct optical behavior.

4.3 Biological Activity

Many zinc (II) ternary complexes demonstrate significant biological activity, including:

- **Antimicrobial properties:** Effective against bacteria and fungi.
- **Anticancer potential:** Some complexes inhibit tumor cell growth by interfering with cellular processes.
- **Enzyme mimicry:** Zinc complexes mimic natural metalloenzymes, facilitating biochemical transformations.

4.4 Catalytic Efficiency

Zinc (II) complexes serve as efficient catalysts in:

- **Organic transformations:** Transesterification, CO_2 fixation, and epoxidation reactions.
- **Environmental applications:** Degradation of pollutants and water purification.

5. Applications

5.1 Biomedical Field

- Zinc (II) complexes are explored as drug delivery systems and imaging agents due to their low toxicity and bioavailability.
- Their ability to bind DNA and proteins opens avenues for therapeutic applications.

5.2 Material Science

- Zinc complexes are incorporated into light-emitting diodes (LEDs) and semiconductors for advanced electronic devices.
- MOFs derived from zinc complexes are used in gas storage and separation.

5.3 Environmental Chemistry

- Zinc (II) complexes catalyze the conversion of greenhouse gases like CO_2 into useful chemicals.
- They are also used in the photodegradation of organic pollutants, aiding environmental remediation.

6. Challenges and Future Directions

6.1 Challenges

- **Selectivity and Reproducibility:** Controlling the formation of specific isomers or geometries during synthesis remains a challenge.
- **Stability:** Zinc (II) complexes may degrade under extreme environmental conditions, limiting their long-term usability.
- **Scalability:** Large-scale synthesis with consistent quality is difficult to achieve.

6.2 Future Directions

- **Ligand Design:** Developing novel ligands with tailored properties to enhance the functionality of zinc complexes.
- **Hybrid Materials:** Integration of zinc complexes into polymeric or inorganic matrices for multifunctional applications.
- **Sustainability:** Emphasis on green synthesis methods and recyclable complexes to align with environmental goals.
- **Computational Studies:** Using quantum chemical methods to predict and rationalize the properties of zinc complexes, guiding experimental efforts.

Conclusion

This review was able to present the synthesis and characterization of zinc (II) ternary complexes with biologically significant ligands, including amino acids, pyridoxine and ampicillin. The synthesis and detailed characterization of these complexes are informative about coordination chemistry, and, in the context of critical global challenges such as sustainable energy, environmental remediation, and advanced therapeutics, provide valuable insights. Results showed stable structures and favorable thermodynamic properties. Spectroscopic and potentiometric analyses showed that ternary complexes were more stable than their respective binary counterparts, consisting in potentials for enzyme mimicking and therapeutical applications, including antimicrobial and anticancer treatments. The coordination of amino acids through the carboxylate and amino groups also highlights their biochemical importance, and the great versatility of zinc (II) complexes in biochemical research.

These results firmly establish a foundation for further development of innovative zinc based biomaterials and pharmaceuticals. Future research employing ecofriendly synthesis techniques, multifunctional hybrid materials design and diverse ligand systems should be prioritized to fully realize the potential of these complexes and their derivatives in next generation technologies and industry.

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