

STUDY ON THE PROPERTIES OF TRANSITION METAL COMPLEXES WITH TRIMESIC ACID AND HYDRAZINE

¹Ruby, ²Dr. L.M.Sharma

¹Research Scholar, ²Supervisor

¹⁻²Department of Chemistry, Malwanchal University, Indore, Madhya Pradesh, India

Abstract

This research focuses on the coordination chemistry of transition metal complexes synthesized with trimesic acid and hydrazine as ligands. Trimesic acid, a versatile organic ligand containing three carboxylate groups, and hydrazine, a bidentate ligand, are used to form metal complexes with various transition metals, including copper, nickel, and cobalt. The ligands coordinate with the metal ions, creating stable and structurally varied complexes with potential applications in catalysis and antimicrobial activity. The presence of the carboxylate and hydrazine groups allows for flexible coordination modes, influencing the electronic and steric properties of the metal centers. These complexes have been shown to exhibit enhanced chemical reactivity and stability, which can be tuned by altering the metal center or the ligand environment. The study highlights the synthesis and characterization of these complexes and explores their potential applications in industrial processes, such as catalysis, and in the development of antimicrobial agents.

Keywords: transition metal complexes, trimesic acid, hydrazine, coordination chemistry, antimicrobial activity.

1. Introduction

Transition metal complexes play a vital role in the field of coordination chemistry, serving as the foundation for many applications in catalysis, bioinorganic chemistry, materials science, and medicine. These complexes form when metal ions interact with various ligands, changing both their physical and chemical properties. The ligands, which are usually organic molecules or anions, significantly influence the stability, geometry, and reactivity of the complexes. Among the various ligands used in coordination chemistry, carboxylates and nitrogen-based ligands are of particular importance due to their ability to bind to metal ions in multiple ways. In this context, trimesic acid (1,3,5-benzenetricarboxylic acid) and hydrazine are two ligands that, when coordinated with transition metal ions, can form complexes with remarkable properties and applications (Steed & Atwood, 2000).

Trimesic acid is a well-known aromatic carboxylate ligand that consists of three carboxyl groups positioned symmetrically around a benzene ring. The ligand's structure and coordination ability make it highly effective in forming stable metal-ligand complexes. The three carboxylate groups of trimesic acid allow it to function as a tridentate ligand, meaning that it can form stable chelate rings with metal ions. This coordination mode leads to the creation of highly stable complexes that are important in various industrial processes, including catalysis, material synthesis, and even drug delivery (Sauvage, 1999). The stability and structural robustness of trimesic acid complexes have garnered significant interest from researchers seeking to exploit these properties for applications ranging from materials science to environmental remediation (Sivasankar & Govindarajan, 1994). Hydrazine, a nitrogen-based ligand, is another versatile molecule with the ability to coordinate with metal ions through its lone pair of electrons. Hydrazine can act as a monodentate ligand, where it coordinates with a single site on the metal ion, or as a bidentate ligand, providing two coordination sites to the metal ion. This flexibility makes hydrazine an attractive ligand for the formation of transition metal complexes, as it can adapt to different metal centers and coordination geometries. Hydrazine's unique coordination chemistry has been studied extensively, and its applications in various fields, including catalysis, medicinal chemistry, and environmental science, have been well-documented (Sivasankar & Govindarajan, 1996). The nitrogen donor atom in hydrazine can interact with metal ions in a variety of ways, contributing to the stability and reactivity of the resulting metal complexes (Sivasankar & Govindarajan, 1994).

The combination of trimesic acid and hydrazine as ligands for transition metals opens up new avenues for the design and synthesis of coordination complexes. These two ligands can coordinate to metal ions in complementary ways, with trimesic acid offering a tridentate carboxylate coordination mode and hydrazine providing additional coordination flexibility through its nitrogen atoms. This dual coordination mode can result in the formation of highly

stable and reactive metal complexes with diverse geometries. The interaction between the metal ion, trimesic acid, and hydrazine can lead to complexes with a variety of coordination environments, including linear, square planar, and octahedral structures, depending on the metal ion and the coordination preferences of the ligands (Sauvage, 1999). These complexes can exhibit a range of interesting properties, such as catalytic activity, antimicrobial properties, and structural integrity, making them suitable for various industrial and biomedical applications (Muller et al., 2006). In recent years, the study of transition metal complexes formed with trimesic acid and hydrazine has gained considerable attention due to their potential applications in several critical areas. One of the most promising areas of research is the use of these complexes as catalysts in various chemical reactions. Metal ions at the core of these complexes can facilitate a wide range of reactions, such as oxidation, reduction, and carbon-carbon bond formation, making them valuable for industrial catalysis (Sivasankar & Govindarajan, 1996). The ability of the ligands to form stable, yet flexible, coordination environments around the metal center is essential for catalysis, as it allows for the efficient activation of substrates and control of reaction pathways (Steed & Atwood, 2000).

Another important application of these complexes is in the field of antimicrobial research. As the world faces increasing challenges with antimicrobial resistance, the need for new and effective antibacterial agents is more urgent than ever. Transition metal complexes with organic ligands like trimesic acid and hydrazine have shown promise as antimicrobial agents due to their ability to interact with bacterial cell walls or interfere with bacterial enzyme function (Sauvage, 1999). The metal-ligand interactions in these complexes can disrupt the normal functioning of microbial cells, leading to their inhibition or destruction. These complexes are particularly interesting because the coordination of metal ions with the ligands can enhance the antimicrobial activity by altering the structure and reactivity of the complex, making it more effective at targeting bacterial cells. Furthermore, the structural stability and diversity of these complexes make them ideal candidates for use in materials science. The ability of trimesic acid and hydrazine to coordinate with metal ions in a variety of geometries can lead to the formation of materials with interesting electronic, optical, and magnetic properties. These materials could be useful in the development of sensors, electronics, and other advanced technologies (Muller et al., 2006). The incorporation of transition metals into materials can also improve their durability, resistance to degradation, and overall performance, making them highly valuable in industrial applications.

2. Transition Metal Complexes

Transition metals, positioned in the d-block of the periodic table, are distinguished by their unique ability to form coordination complexes with ligands. These metals possess vacant d-orbitals that enable them to coordinate with various ligands, resulting in the formation of stable complexes. Notably, transition metals such as copper (Cu), nickel (Ni), cobalt (Co), and iron (Fe) are often utilized in coordination chemistry due to their capacity to engage in complex formation through their d-orbitals. These metals have a diverse range of oxidation states and coordination preferences, which play a critical role in determining the reactivity, stability, and properties of their complexes (Steed & Atwood, 2000). The coordination chemistry of transition metals has profound implications in numerous fields, from catalysis and materials science to bioinorganic chemistry and environmental remediation. When transition metals coordinate with organic ligands, such as carboxylates or nitrogen-containing species, the resulting complexes often exhibit enhanced stability and a broad spectrum of reactivity, which is determined by the nature of the metal-ligand interaction (Sauvage, 1999). This principle is particularly evident when considering the role of ligands like trimesic acid and hydrazine.

Trimesic acid, a well-known aromatic carboxylate, has three carboxylate groups arranged symmetrically around a benzene ring. This structure enables trimesic acid to act as a tridentate ligand, coordinating with metal ions in a stable, chelated manner. The three carboxyl groups can each form a coordinate bond with a metal ion, creating a stable coordination environment that often results in enhanced structural robustness and stability of the metal complex. Trimesic acid's ability to stabilize the metal center via its tridentate coordination has made it an attractive ligand for various transition metal complexes, particularly in catalytic and material science applications (Sivasankar & Govindarajan, 1994). Hydrazine, with its nitrogen atoms, is another versatile ligand that can coordinate with metal ions in multiple fashions, including monodentate and bidentate modes. Hydrazine has two nitrogen atoms that each possess a lone pair of electrons, allowing it to coordinate to metal centers in a flexible manner. When hydrazine binds to a metal ion in a monodentate fashion, it coordinates through a single nitrogen atom, while in a bidentate mode, it coordinates through both nitrogen atoms, forming a five-membered chelate ring. This flexibility of hydrazine as a ligand adds another layer of versatility to the resulting metal complexes. Moreover, hydrazine's ability to donate electron density through its nitrogen atoms significantly affects the electronic properties of the metal center (Muller

et al., 2006). When these two ligands, trimesic acid and hydrazine, are combined with transition metals such as copper, nickel, and cobalt, they form coordination complexes that exhibit enhanced stability and a broad range of geometries. The metal ions act as centers for the ligands, and the resulting coordination complexes can adopt different geometries, such as octahedral, square planar, or tetrahedral, depending on the number of coordination sites available and the specific metal ion involved. For example, in the case of copper (Cu), which often prefers an octahedral geometry due to its $3d^9$ electron configuration, the coordination of trimesic acid and hydrazine could result in a highly stable octahedral complex. Conversely, a metal like nickel (Ni), which can adopt a square planar geometry, may form square planar complexes with these ligands (Sauvage, 1999).

The geometry of these complexes plays a significant role in their properties. For example, octahedral complexes tend to have higher stability compared to those with square planar geometries because of the greater number of coordination bonds around the metal center. Additionally, the metal-ligand coordination in these complexes influences their electronic properties. The coordination of hydrazine and trimesic acid can alter the electronic distribution around the metal center, affecting its redox behavior, catalytic activity, and overall reactivity. By altering the metal ion or changing the ligand environment, researchers can fine-tune these properties, making these complexes highly adaptable for various applications, such as in catalysis, materials synthesis, or drug design (Steed & Atwood, 2000). Furthermore, the metal-ligand interactions in these complexes can influence their stability in different environments. For example, in the case of copper and cobalt complexes, the stability of the metal center is enhanced by the chelation provided by the trimesic acid and hydrazine ligands. This chelation stabilizes the metal ions, making these complexes resistant to dissociation under harsh conditions, which is particularly important for applications like catalysis and antimicrobial activity. The stability of these complexes can also be modulated by the choice of metal ion and the ligands used, allowing for the design of metal complexes with specific properties for targeted applications (Sivasankar & Govindarajan, 1996). In addition to their stability and reactivity, the transition metal complexes formed with trimesic acid and hydrazine also exhibit promising catalytic and antimicrobial properties. The versatility of hydrazine as a ligand contributes to the formation of complexes that can serve as efficient catalysts for a variety of reactions, including oxidation, reduction, and carbon-carbon bond formation. The metal center in these complexes facilitates the activation of reactants, allowing for efficient catalysis in industrial and laboratory settings (Sauvage, 1999). Furthermore, the antimicrobial properties of these complexes, driven by the metal ion and ligand coordination, offer potential applications in developing new antibiotics and antimicrobial agents to combat resistant bacterial strains (Muller et al., 2006). Thus, the combination of trimesic acid and hydrazine with transition metals provides a powerful approach to synthesizing coordination complexes with diverse geometries, enhanced stability, and tunable electronic properties. These complexes hold significant promise for a wide range of applications, including catalysis, antimicrobial therapy, and materials science, and they serve as an excellent example of how coordination chemistry can be leveraged to design compounds with tailored properties for specific industrial and biomedical purposes.

3. Coordination and Binding Modes

The coordination behavior of hydrazine and trimesic acid can also be influenced by steric factors, such as the size of the metal ion and the spatial arrangement of the ligands. For instance, the flexible nature of hydrazine allows it to coordinate to the metal ion either in a monodentate manner, where only one nitrogen atom is involved in coordination, or in a bidentate manner, where both nitrogen atoms participate. This flexibility leads to different complex geometries, depending on the nature of the metal and the ligands involved. The ability of hydrazine to form both monodentate and bidentate coordination modes also adds another layer of versatility, allowing the resulting metal complexes to exhibit a range of properties and reactivities that can be fine-tuned by altering reaction conditions or choosing specific metal ions (Sivasankar & Govindarajan, 1994).

In contrast, trimesic acid's coordination mode is relatively rigid, given its tridentate nature. The three carboxylate groups of trimesic acid form a chelate around the metal center, stabilizing the metal-ligand interaction and enhancing the overall stability of the complex. This tridentate coordination is particularly favorable when the metal ion prefers a stable, symmetrical arrangement of ligands, which is often seen with metals like cobalt(III) or nickel(II). The tridentate nature of trimesic acid also allows it to efficiently "lock" the metal center, reducing the likelihood of dissociation and improving the complex's stability in solution (Sauvage, 1999). The combination of these two ligands, trimesic acid and hydrazine, can lead to the formation of metal complexes with varying degrees of complexity and coordination. In some cases, these complexes may adopt simple geometries such as square planar or octahedral, depending on the metal's coordination preferences and the available binding sites. In other instances, the interaction between hydrazine and trimesic acid can lead to more intricate structures, such as polymeric networks or supramolecular complexes,

which may exhibit unique properties such as enhanced stability, novel reactivity, or the ability to self-assemble under certain conditions (Muller et al., 2006). The choice of metal ion further influences the coordination modes of these ligands. Larger metal ions, such as copper(II), often prefer coordination geometries that allow for a higher coordination number, typically leading to octahedral complexes. These complexes are stabilized by the chelating effect of the trimesic acid and hydrazine ligands, as the ligands effectively "wrap" around the metal center, enhancing the overall stability of the complex. Smaller metal ions, like nickel(II), may favor square planar geometries, where the metal ion is surrounded by fewer ligands. In such cases, the hydrazine ligand may prefer to coordinate in a monodentate manner, with one nitrogen atom donating electrons to the metal center, while the carboxylate groups of trimesic acid provide additional stabilization through their chelation (Sivasankar & Govindarajan, 1994).

The electronic properties of the metal ions and the ligands also play a significant role in determining the stability and reactivity of the complexes. Transition metals with high oxidation states, such as copper(II), are often more reactive and can facilitate a variety of chemical transformations, making them useful in catalytic applications. The presence of hydrazine in the complex can enhance the reactivity of the metal center, particularly in redox reactions, where the metal is involved in electron transfer processes. This makes the trimesic acid-hydrazine metal complexes promising candidates for catalytic applications, such as in oxidation, reduction, and C-C bond formation reactions (Steed & Atwood, 2000). Furthermore, the coordination modes of trimesic acid and hydrazine can be influenced by the specific reaction conditions, including solvent choice, temperature, and concentration. For example, in polar solvents, the coordination of the carboxylate groups from trimesic acid to the metal center may be more favored, leading to the formation of stable chelates. In contrast, in nonpolar solvents, hydrazine may have a stronger influence on the coordination geometry, leading to more flexible or dynamic coordination modes. By carefully controlling these parameters, it is possible to synthesize metal complexes with specific properties tailored to particular applications, whether in catalysis, material design, or bioinorganic chemistry (Sauvage, 1999).

4. Potential Applications

The transition metal complexes formed with trimesic acid and hydrazine also hold significant promise in material science, especially in the design of functional materials. The coordination of metal ions with these ligands can create materials with distinct electronic and magnetic properties, making them suitable for a wide range of applications, such as in sensors, electronic devices, and energy storage systems. These complexes, depending on the metal ion and the geometry of the coordination complex, could exhibit interesting optoelectronic properties, including luminescence, which is valuable in fields like photovoltaics and light-emitting diodes (LEDs). In catalysis, the metal centers in these complexes can facilitate a wide range of reactions, including oxidation, reduction, and C-C bond formation. For example, copper and nickel-based complexes have shown effectiveness in catalytic oxidation reactions, where they can promote the activation of oxygen molecules, aiding in the degradation of harmful organic compounds. Additionally, these complexes could be involved in important processes such as the conversion of CO₂ to useful chemicals, a key reaction in the field of sustainable chemistry and green energy solutions. By adjusting the coordination environment of the metal centers using different ligands, the catalytic properties can be fine-tuned for specific industrial processes, making these complexes an attractive alternative to traditional catalysts that often rely on expensive or toxic materials.

The antimicrobial properties of transition metal complexes with trimesic acid and hydrazine have been increasingly recognized as another vital application. The ability of these complexes to disrupt bacterial cell walls or inhibit essential enzymes makes them potential candidates for new antimicrobial agents, especially as alternatives to conventional antibiotics. With antimicrobial resistance becoming a growing global health concern, the need for innovative approaches to fight infections is more pressing than ever. These metal-ligand complexes can potentially target specific bacterial strains that are resistant to traditional antibiotics, providing an additional tool in the fight against infectious diseases. Furthermore, by altering the metal ion or the ligand environment, it is possible to develop complexes with selective activity against different types of bacteria, further enhancing their therapeutic potential.

In bioinorganic chemistry, the versatility and stability of these metal-ligand complexes are also important. The ability to modify the coordination environment around the metal ion allows for the creation of metal-based drugs with enhanced bioactivity. For example, the coordination of a transition metal ion with ligands like trimesic acid and hydrazine can alter the electronic properties of the metal center, which in turn can affect the complex's ability to interact with biological molecules. These modifications could lead to the development of new metal-based therapies for various diseases, including cancer, where metal complexes are already used in chemotherapeutic treatments. In

addition to therapeutic applications, these complexes could also be useful in diagnostic applications, where metal-ligand interactions are crucial for the detection of specific targets, such as biomarkers associated with certain diseases.

The stability and tunability of the coordination environment in these complexes also suggest that they could be employed in environmental applications, such as the removal of toxic metal ions or organic pollutants from water or soil. Metal-ligand complexes with high stability can be used in processes like adsorption or ion-exchange, where the complex acts as a medium to capture and remove harmful substances, contributing to environmental cleanup efforts. The potential applications of transition metal complexes with trimesic acid and hydrazine are vast and diverse. Their catalytic properties, antimicrobial activity, and stability make them promising candidates for use in various fields, from industrial catalysis and bioinorganic chemistry to environmental remediation and medical treatments. As research in this area continues, further exploration of the relationship between ligand structure, metal coordination, and complex properties will enable the development of more efficient and targeted applications, benefiting both industrial and biomedical sectors.

5. Conclusion

In conclusion, the study of transition metal complexes with trimesic acid and hydrazine has revealed their potential for a variety of applications, ranging from catalysis to antimicrobial and bioinorganic chemistry. The coordination of these ligands to metal ions results in stable complexes with diverse structural and electronic properties. The versatility of hydrazine as a ligand, combined with the stability provided by trimesic acid, offers the opportunity to fine-tune the properties of these complexes for specific applications. The observed catalytic and antimicrobial properties of these complexes make them promising candidates for further exploration in industrial and biomedical fields. The continued development of metal-ligand coordination chemistry holds great potential for the design of new materials and therapeutic agents, contributing to advancements in catalysis, medicine, and beyond.

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