ISSN: 2707-1146
e-ISSN: 2709-4189

DOI: https://doi.org/10.36719/2707-1146/61/27-30

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Application Prospects of Hydrazone-Based Organic Ligands

Abstract

Hydrazone-based organic ligands represent a versatile class of compounds that have gained considerable attention in coordination chemistry and medicinal research due to their unique structural features and diverse functional properties. These ligands, characterized by the presence of an azomethine (–C=NNH–) group, can act as nitrogen–nitrogen donor systems, facilitating the formation of stable complexes with a wide range of metal ions. Recent studies have highlighted their potential in catalysis, metal sensing, and drug design, including antimicrobial, antifungal, and anticancer applications. The tunability of substituents on the hydrazone backbone allows for modulation of both electronic and steric properties, thereby influencing the stability, selectivity, and biological activity of the resulting complexes. This review systematically examines the recent advances in the synthesis, coordination behavior, and application prospects of hydrazone-based ligands. Key trends in ligand design, structure–activity relationships, and emerging therapeutic and industrial applications are discussed. This research provides a systematic review of the existing literature, revealing the promising possibilities of hydrazone ligands as functional molecules in organic synthesis and biomedicine.

Keywords: *hydrazone, ligand, complexes, organic synthesis, catalysis, biological activity, medicine*

Introduction

Hydrazones are a class of organic compounds formed by the condensation of carbonyl compounds with hydrazine and have the general formula $R_1R_2C=NNH_2$. These compounds contain a nitrogen–nitrogen (–N=NH–) bond, which gives their chemical properties a unique dynamism and reactivity. Hydrazones can be stable both free and in the form of complexes with metal ions. Their structural flexibility and functional diversity make hydrazones suitable for a wide range of applications in chemistry, materials science, and biotechnology (Abd El-Wahab, 2015).

The structure of hydrazones can be modified by both electronic and steric factors. These modifications change their coordination behavior, protonation ability, and electron donor/acceptor properties. These properties make hydrazones attractive for the synthesis of organometallic complexes and for the preparation of various catalytic and functional materials. In recent years, hydrazones have gained relevance as objects of research in organic and coordination chemistry. Their ability to complex with various metal ions, as well as their tautomeric and conjugation properties, are of interest in terms of chemical reactivity and stability. Hydrazones are also applied as key components in molecular engineering, material design, and sensor technologies.

Structurally, hydrazones can be synthesized as aromatic and aliphatic derivatives. Hydrazones combined with aromatic systems form more stable and colorful complexes, while aliphatic hydrazones are more reactive and allow for various chemical transformations. This structural flexibility allows researchers to design hydrazones for specific purposes. Hydrazones can also act as proton and electron acceptors and donors, which makes them important actors in redox and coordination chemistry. These properties make hydrazones have a wide range of applications in catalysis, sensors, polymer and material science. Thus, hydrazone-based organic ligands are relevant as a multidisciplinary research object in various fields of chemistry.

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Their chemical structure, coordination ability, and functional flexibility make them even more important for both fundamental and applied research.

Materials and Methods

This study mainly used the method of theoretical generalization of scientific literature. The synthesis methods, chemical properties, and practical applications of hydrazone derivatives presented in various studies were systematized and analyzed.

From a methodological point of view, the article covers three directions:

- Structural analysis: Functional groups of hydrazones and their complexation mechanisms with metal ions were reviewed.
- Application directions: Information on their use in biological, catalytic, and material sciences was grouped.
- Perspective approaches: Analytical results on the future applications of hydrazones in green chemistry and nanotechnology were presented.

Research

Biological and pharmacological importance. Hydrazone derivatives are one of the most studied organic classes in terms of biological activity. Since their structure can be modified both electronically and sterically, they can be directed against various biological targets (Shikhaliyev, 2025). This property makes hydrazones suitable for use as antimicrobial, antiviral, antifungal, and antitumor agents (Mathew, 2015). Analyses of the intracellular mechanisms of hydrazone–metal complexes have shown that these compounds reduce cellular stress and activate apoptotic mechanisms by regulating the generation of reactive oxygen species (Charan, 2025). In particular, Cu(II), Ni(II), Zn(II), and Fe(III) complexes have demonstrated high anticancer activity. In addition, hydrazones can also act as enzyme inhibitors, which is considered an important direction in the design of new pharmacological drugs (Guimaraes, 2017).

Importance in catalytic and synthetic chemistry. Hydrazone ligands play an important role in both homogeneous and heterogeneous processes in catalytic systems. They stabilize the coordination of transition metals, increase the selectivity of reactions, and enable the formation of energy -efficient mechanisms. For example, hydrazone-based catalysts provide high yields and selectivity in three-component reactions of type A^3 (consisting of aldehyde, amine, and alkyne) (Mali, 2021). In addition, these ligands are also effective in carbon–hydrogen functionalization, oxidation, and reduction reactions. Another area of particular importance in terms of catalysis is the chemical fixation of carbon dioxide (CO_2) (Xu, 2018). The electron donor–acceptor properties of hydrazone derivatives facilitate the activation of CO_2 molecules and their conversion into various organic compounds. This is important in terms of the development of environmentally safe, sustainable processes in the direction of green chemistry (Sun, 2025).

Application in materials science and nanotechnology. The application of hydrazones in materials science has increased dramatically in recent years. Polymers with hydrazone functional groups, when complexed with metals, form materials with high mechanical strength and thermal stability (Tai, 2018). Hydrazone bonds are also used as the main connecting element in the construction of covalent organic frameworks (COFs). Such COFs have important potential in gas adsorption, energy storage, and ion exchange systems. The role of hydrazones in the synthesis of nanomaterials is even broader. Their reducing and directing properties allow controlling the morphology of metal and semiconductor nanoparticles. For example, in the formation of materials such as ZnSe and CdS, hydrazones help control particle size and surface morphology. These properties open up new possibilities for important applications in the fields of optoelectronics and photocatalysis (Florence, 2015).

Analytical and environmental chemistry directions. Hydrazone derivatives are widely used as analytical reagents with high selectivity and sensitivity. Their main application is the determination and monitoring of metal ion concentrations (Hanif, 2019). Hydrazone sensors, which act as fluorescent and color indicators, are effective in detecting ions such as Zn^{2+}, Cu^{2+}, Fe^{3+}, and Hg^{2+}. The advantage of hydrazone-based sensors is that they remain stable in the aquatic environment and

 ISSN: 2707-1146
e-ISSN: 2709-4189

provide results in a short time. This makes it possible to use them in ecological analysis systems to determine the level of environmental pollution (Jabeen, 2022).

Industry and polymer technology. Hydrazone compounds are widely used in industry as polymer stabilizers, adhesives, textile modifiers, and corrosion inhibitors. Their chemical stability and heat resistance make hydrazones suitable for the preparation of long-lasting materials. In addition, some hydrazone derivatives have photoreactive and color-changing properties, which make them promising components in the design of optical sensors and smart materials (Zhuang, 2024).

Conclusion

The conducted analyses show that hydrazone-based compounds have a wide range of application potential. Structural flexibility and chemical stability make this class promising for the creation of functional materials in various fields — especially in catalysis, medicinal chemistry, materials science, and analytical chemistry. The ability of hydrazones to form complexes with metal ions makes them important both as the main component of catalytic systems and as a component of biologically active substances. In terms of biological activity, the enzyme-inhibitory, antimicrobial, and antitumor properties of hydrazone derivatives make them suitable for use in drug design. Increasing selectivity and reducing toxicity through structural modifications further strengthens the importance of these compounds in clinical and molecular biology research.

The application of hydrazone ligands in catalytic processes increases the selectivity and efficiency of reactions and ensures the stability of metal complexes. In particular, in reactions such as C–H functionalization, oxidation–reduction, and chemical fixation of carbon dioxide, hydrazones allow the construction of sustainable catalytic systems in accordance with the principles of green chemistry.

In the field of materials science, the use of hydrazone-based covalent organic frameworks and polymers in the fields of energy storage, gas adsorption, ion exchange, and nanomaterial synthesis promises important results. Controlling the morphological properties of these materials opens up a wide range of applications in photocatalysis, optoelectronics, and sensor technology.

In analytical chemistry, the use of hydrazone derivatives as reagents with high selectivity and sensitivity increases their importance in the detection of metal ions and environmental monitoring.

Overall, future research on hydrazone-based compounds should focus on a deeper understanding of their structure–function relationships and the design of new functional materials and environmentally sustainable systems. Research in the fields of molecular engineering, nanomaterial synthesis, and biological applications will further strengthen the strategic role of hydrazones in science and industry.

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Received: 15.06.2025
Accepted: 23.09.2025