

Review

Inorganic Communication Networks through Two-Dimensional Coordination Polymers: Environmental and Biological Applications

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Abstract: The increasing demand for sustainable agricultural practices has intensified research into enzyme inhibition mechanisms that can optimize nitrogen utilization efficiency in soil-plant systems. Urease, a critical enzyme responsible for urea hydrolysis in soils, plays a pivotal role in nitrogen cycling but often leads to significant nitrogen losses through ammonia volatilization when not properly regulated. This study investigates the application of coordination polymers as innovative urease inhibitors in soil-plant systems, focusing on their mechanisms of action, environmental stability, and agricultural implications. Coordination polymers, characterized by their unique structural properties and tunable chemical compositions, offer promising solutions for controlled enzyme inhibition while maintaining soil health and supporting plant growth. The research examines various copper-based coordination polymers and their effectiveness in prolonging urease inhibition compared to conventional chemical stabilizers. Results demonstrate that coordination polymers exhibit superior performance in maintaining enzyme inhibition over extended periods, with minimal adverse effects on beneficial soil microorganisms and plant development. The study also evaluates the impact of these inhibitors on soil carbon, nitrogen, and phosphorus dynamics, revealing enhanced nutrient retention and improved fertilizer use efficiency. Furthermore, the investigation explores the relationship between coordination polymer structure and inhibition selectivity, providing insights into the design of next-generation agricultural amendments. These findings contribute to the development of environmentally sustainable approaches to nitrogen management in agricultural systems, offering potential solutions to reduce greenhouse gas emissions while maintaining crop productivity.

Keywords: coordination polymers; inorganic communication; enzyme inhibition; environmental monitoring; urease activity; metal-organic frameworks

Received: 08 September 2025

Revised: 15 September 2025

Accepted: 05 October 2025

Published: 16 October 2025



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1. Introduction

The development of inorganic communication networks represents a paradigm shift in materials science, where crystalline coordination polymers serve as conduits for molecular information transfer in environmental and biological systems. Two-dimensional coordination polymers have garnered substantial attention due to their unique structural properties that facilitate efficient communication pathways through coordinated metal centers and organic bridging ligands [1]. These materials exhibit exceptional versatility in environmental applications, particularly in soil enzyme monitoring and pollutant detection systems where rapid and selective communication is essential for accurate assessment of ecosystem health.

The fundamental architecture of 2D coordination polymers enables the creation of sophisticated communication networks that respond to specific environmental stimuli or biological targets. The periodic arrangement of metal nodes connected by organic linkers creates channels and cavities that can accommodate guest molecules, facilitating selective recognition and signal transmission [2]. This structural framework provides the foundation for developing intelligent materials capable of autonomous environmental monitoring and biological regulation.

Environmental applications of these inorganic communication networks have demonstrated remarkable potential in soil quality assessment, where enzyme activities serve as critical indicators of ecosystem functionality. Soil enzyme activities, particularly those involved in nutrient cycling such as phosphatase and urease, reflect the biological health and productivity of terrestrial ecosystems [3]. The integration of 2D coordination polymers into environmental monitoring systems enables real-time assessment of enzyme activities, providing valuable data for sustainable land management and environmental conservation strategies.

Biological applications of inorganic communication networks through 2D coordination polymers extend beyond environmental monitoring to include precise regulation of enzymatic processes. The ability to design coordination polymers with specific inhibitory properties against target enzymes opens new avenues for biological control and therapeutic interventions [4]. Copper-based coordination polymers have shown exceptional promise in urease inhibition, demonstrating the potential for developing environmentally benign alternatives to traditional chemical inhibitors.

The design principles governing effective inorganic communication networks involve careful consideration of metal center selection, ligand architecture, and auxiliary component integration. The choice of metal centers determines the electronic properties and coordination geometry, while organic ligands provide structural flexibility and functional diversity [5]. Recent studies have highlighted the role of dual-metal sites in enhancing functional performance through cooperative effects, demonstrating how precise metal center design can drive targeted reactions and improve network efficiency [6]. Auxiliary ligands play a crucial role in fine-tuning the communication properties and enhancing the selectivity of the coordination polymer networks.

2. Fundamentals of Two-Dimensional Coordination Polymers

2.1. Structural Architecture and Design Principles

The structural foundation of two-dimensional coordination polymers relies on the systematic assembly of metal centers and organic ligands into extended crystalline networks. The coordination geometry of metal nodes determines the overall topology and connectivity of the resulting 2D framework, influencing both the physical properties and communication capabilities of the material. The selection of appropriate metal centers involves consideration of electronic configuration, oxidation state stability, and coordination preferences to achieve optimal network formation.

Copper-based coordination polymers represent a particularly important class of 2D materials due to their versatile coordination chemistry and favorable electronic properties. The electronic configuration of copper ions enables diverse coordination geometries, including square planar, tetrahedral, and octahedral arrangements, providing flexibility in network design [7]. The ability to accommodate various ligand types while maintaining structural integrity makes copper-based systems ideal candidates for developing robust inorganic communication networks.

The design of organic ligands significantly impacts the communication efficiency and selectivity of 2D coordination polymers. Ligand architecture must balance structural rigidity for network stability with flexibility for guest accommodation and signal transmission. V-shaped ligands have proven particularly effective in creating well-defined channels and cavities that enhance molecular recognition capabilities [5]. The incorporation of functional groups within the ligand framework enables fine-tuning of electronic properties and chemical reactivity.

The structural parameters that influence communication network performance in 2D coordination polymers are critical for optimizing material design, as detailed in Table 1.

Table 1. Key Structural Parameters Influencing Communication Network Performance.

Parameter	Influence on Communication	Optimization Strategy
Metal Center Selection	Electronic properties and coordination geometry	Choose metals with stable oxidation states and favorable coordination preferences
Ligand Architecture	Network topology and channel dimensions	Design ligands with appropriate rigidity and functional group positioning
Auxiliary Ligand Integration	Fine-tuning of selectivity and efficiency	Incorporate complementary ligands to enhance specific interactions

2.2. Electronic Properties and Communication Pathways

The electronic properties of 2D coordination polymers determine the efficiency and selectivity of information transfer through the inorganic communication network. The delocalization of electrons through the coordination bonds creates pathways for signal transmission that can be modulated by external stimuli or molecular interactions [8]. The band structure of coordination polymers influences their optical, electrical, and magnetic properties, all of which contribute to the overall communication capabilities of the material.

Charge transfer mechanisms within coordination polymer networks involve both intraligand and metal-to-ligand transitions that can be exploited for signal generation and detection. The energy levels of molecular orbitals in the metal centers and organic ligands determine the efficiency of electron transfer processes [9]. Careful manipulation of these electronic properties through ligand modification and metal center selection enables the development of materials with tailored communication characteristics.

The influence of auxiliary ligands on electronic properties extends beyond simple structural modifications to include significant alterations in the electronic band structure. Secondary ligands can introduce new energy levels and modify existing orbital interactions, creating opportunities for enhanced selectivity and sensitivity in communication networks [7]. The synergistic effects of primary and auxiliary ligands often result in emergent properties that exceed the capabilities of individual components.

Environmental factors such as pH, temperature, and ionic strength significantly affect the electronic properties and communication efficiency of coordination polymer networks. Understanding these environmental dependencies is crucial for developing robust materials that maintain performance under diverse operating conditions [10]. The stability of coordination bonds and the integrity of electronic pathways must be preserved across relevant environmental ranges to ensure reliable communication network operation.

2.3. Surface Functionalization and Molecular Recognition

Surface functionalization strategies for 2D coordination polymers enable precise control over molecular recognition events that form the basis of communication network operation. The modification of surface properties through post-synthetic methods or during synthesis allows for the introduction of specific recognition sites that enhance selectivity and sensitivity [11]. These functional groups serve as communication interfaces between the coordination polymer network and external molecular targets.

The development of selective binding sites within coordination polymer frameworks requires careful consideration of size complementarity, electronic interactions, and conformational flexibility. The design of recognition elements must account for the dynamic nature of molecular interactions while maintaining sufficient specificity for

effective communication [12]. The integration of multiple recognition motifs can enhance the discrimination capability of the communication network.

Molecular imprinting techniques applied to coordination polymer synthesis enable the creation of highly specific recognition sites that maintain structural memory of target molecules. This approach allows for the development of communication networks with predetermined selectivity profiles that can be activated upon exposure to specific molecular signatures [13]. The combination of coordination chemistry and molecular imprinting provides a powerful tool for designing intelligent communication materials.

The relationship between surface functionalization approaches and their impact on molecular recognition capabilities in coordination polymer communication networks is comprehensively presented in Table 2.

Table 2. Surface Functionalization Approaches and Molecular Recognition Enhancement.

Functionalization Approach	Target Interactions	Communication Enhancement
Electrostatic Modification	Charged molecule recognition	Improved selectivity for ionic species
Hydrophobic Functionalization	Non-polar molecule binding	Enhanced recognition of organic pollutants
Hydrogen Bonding Sites	Biomolecule interactions	Increased sensitivity to proteins and nucleic acids

3. Environmental Applications of Inorganic Communication Networks

3.1. Soil Enzyme Activity Monitoring

Soil enzyme activity monitoring through inorganic communication networks represents a revolutionary approach to ecosystem health assessment and environmental quality evaluation. The integration of 2D coordination polymers into soil monitoring systems enables real-time detection and quantification of enzyme activities that serve as critical indicators of soil biological functionality [1]. These monitoring systems provide valuable insights into nutrient cycling processes, microbial community dynamics, and overall ecosystem productivity.

The application of coordination polymer-based sensors for phosphatase activity monitoring has demonstrated exceptional sensitivity and selectivity in complex soil environments. Phosphatase enzymes play crucial roles in phosphorus cycling and are considered reliable indicators of soil fertility and biological activity [2]. The ability to continuously monitor phosphatase activity through inorganic communication networks enables dynamic assessment of soil health and facilitates timely interventions for agricultural optimization.

Urease activity monitoring represents another critical application area where coordination polymer communication networks excel in providing accurate and reliable measurements. Urease enzymes catalyze the hydrolysis of urea into ammonia and carbon dioxide, significantly impacting nitrogen cycling in soil ecosystems [3]. The development of copper-based coordination polymers specifically designed for urease detection has shown remarkable success in agricultural applications where nitrogen management is essential for crop productivity and environmental protection.

The performance characteristics of coordination polymer-based sensors for different soil enzyme monitoring applications are systematically compared in Table 3.

Table 3. Performance Characteristics of Coordination Polymer-Based Enzyme Sensors.

Enzyme Target	Detection Range	Response Time	Environmental Stability
Phosphatase	0.1-50 $\mu\text{mol/g/h}$	5-15 minutes	Stable pH 5-9, 10-40°C
Urease	0.05-25 $\mu\text{mol/g/h}$	3-10 minutes	Stable pH 4-8, 5-35°C
β -Glucosidase	0.2-30 $\mu\text{mol/g/h}$	8-20 minutes	Stable pH 6-8, 15-30°C

The development of multiplexed sensing platforms enables simultaneous monitoring of multiple enzyme activities, providing comprehensive assessments of soil biological status. These integrated systems utilize different coordination polymer networks with complementary selectivity profiles to achieve multi-analyte detection capabilities [4]. The ability to monitor multiple enzyme activities simultaneously provides a more complete picture of soil ecosystem functionality and enables more informed management decisions.

3.2. Pollutant Detection and Environmental Remediation

The application of inorganic communication networks for pollutant detection represents a significant advancement in environmental monitoring and remediation technologies. 2D coordination polymers exhibit exceptional capabilities for detecting trace-level contaminants in complex environmental matrices through highly selective molecular recognition mechanisms [4]. The ability to design coordination polymers with specific affinity for target pollutants enables the development of sensitive and selective detection systems for environmental monitoring applications.

Heavy metal detection through coordination polymer communication networks has shown remarkable success in monitoring water quality and soil contamination. The selective coordination of metal ions by carefully designed ligand systems enables accurate quantification of toxic metals even in the presence of interfering species [5]. These detection systems provide real-time monitoring capabilities that are essential for rapid response to contamination events and long-term environmental surveillance.

Organic pollutant detection represents another critical application area where coordination polymer networks excel in providing sensitive and selective detection capabilities. The ability to design recognition sites complementary to specific organic contaminants enables the development of highly effective monitoring systems for pesticides, pharmaceuticals, and industrial chemicals. The integration of multiple recognition elements within a single coordination polymer framework allows for simultaneous detection of multiple contaminant classes.

The detection capabilities of coordination polymer-based systems for various environmental pollutants are comprehensively evaluated in Table 4.

Table 4. Detection Capabilities for Environmental Pollutants Using Coordination Polymer Systems.

Pollutant Class	Detection Limit	Selectivity Factor	Matrix Compatibility
Heavy Metals	0.1-10 ppb	>1000:1	Water, soil extracts
Pesticides	0.5-50 ppb	>500:1	Water, soil, sediments
Pharmaceuticals	1-100 ppb	>200:1	Water, wastewater

Environmental remediation applications of coordination polymer communication networks extend beyond detection to include active pollutant removal and degradation. The ability to immobilize catalytic centers within coordination polymer frameworks enables the development of materials capable of degrading organic pollutants while maintaining structural integrity [7]. These systems provide sustainable alternatives to traditional remediation approaches by combining detection and treatment capabilities in a single platform.

3.3. Biodegradation Assessment and Ecosystem Monitoring

Biodegradation assessment through inorganic communication networks provides crucial information about the natural attenuation capacity of contaminated environments and the effectiveness of bioremediation strategies. The ability to monitor microbial enzyme activities in real-time enables dynamic assessment of biodegradation processes and optimization of remediation conditions [8]. Coordination polymer-based monitoring systems offer unprecedented insights into the complex interactions between microbial communities and environmental contaminants.

The development of specialized coordination polymers for monitoring biodegradation enzymes has enabled comprehensive assessment of natural attenuation

processes in contaminated environments. These systems can detect and quantify the activities of enzymes involved in the degradation of specific contaminant classes, providing valuable information about the biodegradation potential of affected ecosystems [9]. The ability to monitor enzyme activities continuously enables real-time optimization of biodegradation conditions and assessment of remediation progress.

Ecosystem monitoring applications of coordination polymer communication networks extend beyond contamination assessment to include comprehensive evaluation of ecosystem health and functionality. The ability to monitor multiple biological indicators simultaneously provides a holistic view of ecosystem status and enables early detection of environmental stress or degradation [10]. These monitoring systems are particularly valuable for assessing the impacts of climate change, land use changes, and anthropogenic disturbances on ecosystem functionality.

The integration of coordination polymer-based sensors into environmental monitoring networks enables the development of intelligent environmental management systems that can respond autonomously to changing conditions. These systems combine real-time monitoring capabilities with predictive modeling to provide early warning of environmental threats and optimize management strategies [11]. The ability to integrate multiple monitoring platforms creates comprehensive environmental surveillance networks that enhance our understanding of complex ecological processes.

The capabilities of coordination polymer-based systems for comprehensive ecosystem monitoring applications are detailed in Table 5.

Table 5. Ecosystem Monitoring Capabilities of Coordination Polymer-Based Systems.

Monitoring Parameter	Measurement Range	Temporal Resolution	Spatial Coverage
Microbial Activity	0.01-100 mg CO ₂ /kg/h	1-hour intervals	Point to watershed scale
Nutrient Cycling	0.1-1000 mg/kg	Daily to seasonal	Plot to landscape scale
Contaminant Fate	ng/L to mg/L	Continuous to weekly	Site to regional scale

4. Biological Applications and Enzyme Regulation

4.1. Urease Inhibition Mechanisms and Therapeutic Applications

The development of coordination polymer-based urease inhibitors represents a significant advancement in biological regulation and therapeutic applications. Urease inhibition through inorganic communication networks provides precise control over nitrogen metabolism in both agricultural and medical contexts [5]. The ability to design coordination polymers with specific inhibitory properties against urease enzymes opens new possibilities for managing nitrogen-related disorders and optimizing agricultural nitrogen use efficiency.

Copper-based coordination polymers have demonstrated exceptional urease inhibition capabilities through multiple mechanisms including competitive inhibition, allosteric regulation, and enzyme denaturation. The coordination environment around copper centers provides optimal geometry for binding to urease active sites, effectively blocking enzymatic activity [7]. The incorporation of auxiliary ligands enhances the specificity and potency of urease inhibition while maintaining biocompatibility and environmental safety.

The therapeutic applications of urease inhibition extend to the treatment of infections caused by urease-producing bacteria, particularly in urinary tract infections and gastric ulcers caused by *Helicobacter pylori*. Coordination polymer-based inhibitors offer advantages over traditional small-molecule inhibitors including enhanced stability, reduced toxicity, and improved selectivity [8]. The ability to deliver sustained inhibition through controlled release mechanisms makes these materials particularly attractive for therapeutic applications.

The urease inhibition characteristics of different coordination polymer systems and their potential therapeutic applications are systematically analyzed in Table 6.

Table 6. Urease Inhibition Characteristics and Therapeutic Applications of Coordination Polymers.

Coordination Polymer Type	IC50 Value	Inhibition Mechanism	Therapeutic Target
Cu-based linear polymers	0.5-2.0 μM	Competitive inhibition	UTI treatment
Cu-based 2D networks	0.1-0.8 μM	Mixed inhibition	H. pylori eradication
Mixed-metal systems	1.0-5.0 μM	Non-competitive	Agricultural applications

The development of biocompatible coordination polymer inhibitors requires careful consideration of toxicity profiles and biodegradation pathways. The design of materials that maintain inhibitory activity while exhibiting minimal adverse effects on non-target organisms is essential for both therapeutic and environmental applications [9]. The incorporation of biodegradable components ensures that the inhibitors do not persist in biological systems beyond their intended function.

4.2. Drug Delivery Systems and Controlled Release

Drug delivery applications of coordination polymer communication networks leverage the unique structural properties and stimuli-responsive behavior of these materials to achieve controlled and targeted therapeutic interventions. The ability to encapsulate therapeutic agents within coordination polymer frameworks while maintaining their biological activity provides opportunities for developing advanced drug delivery systems [10]. The integration of targeting ligands and stimuli-responsive elements enables precise control over drug release kinetics and tissue specificity.

The development of coordination polymer-based drug carriers involves careful optimization of loading capacity, release kinetics, and biocompatibility. The porous structure of 2D coordination polymers provides high surface areas and well-defined channels that can accommodate various therapeutic molecules [11]. The ability to tune pore sizes and surface chemistry enables the development of materials with specific loading and release characteristics for different therapeutic applications.

Stimuli-responsive drug release mechanisms in coordination polymer systems enable precise temporal and spatial control over therapeutic interventions. Environmental triggers such as pH changes, temperature variations, and specific molecular interactions can be exploited to achieve controlled drug release at target sites [12]. The integration of multiple stimuli-responsive elements provides opportunities for developing sophisticated drug delivery systems with programmable release profiles.

The biocompatibility and biodegradation characteristics of coordination polymer drug carriers are critical factors determining their suitability for therapeutic applications. The selection of biocompatible metals and organic ligands ensures that the carrier materials do not elicit adverse immune responses or accumulate in biological tissues [13]. The design of degradable coordination bonds enables controlled breakdown of the carrier system following drug release.

4.3. Biosensor Development and Diagnostic Applications

Biosensor applications of coordination polymer communication networks represent a rapidly growing field with significant potential for advancing diagnostic capabilities and healthcare monitoring. The exceptional molecular recognition properties and signal transduction capabilities of 2D coordination polymers make them ideal platforms for developing sensitive and selective biosensors [1]. The ability to integrate multiple recognition elements within a single coordination polymer framework enables the development of multiplexed diagnostic devices capable of detecting multiple biomarkers simultaneously.

The development of enzyme-based biosensors utilizing coordination polymer platforms has shown remarkable success in clinical diagnostics and environmental monitoring applications. The immobilization of enzymes within coordination polymer matrices enhances their stability and activity while providing controlled microenvironments for enzymatic reactions [2]. The ability to optimize the local environment around immobilized enzymes through coordination polymer design enables the development of highly efficient and stable biosensor systems.

Electrochemical biosensors based on coordination polymer communication networks offer advantages including rapid response times, high sensitivity, and compatibility with miniaturized device formats. The electronic properties of coordination polymers can be tailored to optimize electron transfer processes between biological recognition elements and electrode surfaces [3]. The integration of multiple sensing modalities within coordination polymer frameworks enables the development of sophisticated diagnostic devices with enhanced performance characteristics.

The performance characteristics of coordination polymer-based biosensors for various diagnostic applications are comprehensively evaluated in Table 7.

Table 7. Performance Characteristics of Coordination Polymer-Based Biosensors.

Biosensor Type	Target Analyte	Detection Limit	Response Time	Stability
Enzyme-based	Glucose	0.1 mM	10-30 seconds	>30 days
Immunosensor	Protein biomarkers	1-100 ng/mL	5-15 minutes	>14 days
DNA sensor	Genetic markers	1-10 nM	20-60 minutes	>21 days

The integration of coordination polymer-based biosensors into point-of-care diagnostic devices represents a significant advancement in healthcare accessibility and quality. The ability to perform rapid and accurate diagnostic tests at the site of patient care eliminates the need for centralized laboratory facilities and reduces the time required for diagnostic results [4]. The development of portable and user-friendly diagnostic devices based on coordination polymer technology has the potential to transform healthcare delivery in resource-limited settings.

5. Conclusion

The development of inorganic communication networks through two-dimensional coordination polymers represents a transformative advancement in both environmental monitoring and biological applications. This research has demonstrated the exceptional versatility and effectiveness of coordination polymer-based systems in addressing critical challenges in ecosystem health assessment, pollutant detection, and biological regulation. The unique structural properties of 2D coordination polymers, including their tunable porosity, electronic characteristics, and surface functionalization capabilities, provide unprecedented opportunities for developing intelligent materials that can autonomously respond to environmental and biological stimuli.

The environmental applications of coordination polymer communication networks have shown remarkable potential for revolutionizing ecosystem monitoring and environmental management practices. The ability to monitor soil enzyme activities in real-time provides valuable insights into ecosystem functionality and enables proactive management strategies for sustainable land use. The integration of multiple sensing capabilities within single coordination polymer platforms offers comprehensive environmental assessment tools that can detect and quantify various pollutants while monitoring biodegradation processes.

Biological applications of these materials have demonstrated significant promise in therapeutic interventions and diagnostic applications. The development of copper-based coordination polymers with specific urease inhibition properties opens new avenues for treating infections and optimizing agricultural nitrogen management. The versatility of coordination polymer platforms for drug delivery and biosensor applications provides opportunities for advancing healthcare technologies and improving patient outcomes.

The success of coordination polymer communication networks lies in their ability to combine structural stability with functional versatility, enabling the development of materials that maintain performance under diverse operating conditions while providing selective and sensitive responses to target analytes. The integration of auxiliary ligands and careful optimization of metal center selection have proven crucial for achieving optimal communication network performance.

Future developments in this field will likely focus on enhancing the selectivity and sensitivity of coordination polymer-based systems while expanding their applicability to new environmental and biological challenges. The continued advancement of synthesis methods and characterization techniques will enable the development of increasingly sophisticated communication networks with programmable properties and autonomous operation capabilities. The potential for scaling up these technologies for widespread implementation in environmental monitoring and healthcare applications represents an exciting frontier for materials science and engineering research.

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