Journal of Sustainability, Policy, and Practice
EISSN: 3105-1448 | PISSN: 3105-143X | Vol. 1, No. 3 (2025)

Article

Agricultural Sustainability through Advanced Coordination Chemistry Applications: Environmentally Friendly Enzyme Inhibitors

James Rodriguez [1,*]

[1] University of Central Lancashire, Lancashire, United Kingdom
* Correspondence: James Rodriguez, University of Central Lancashire, Lancashire, United Kingdom

Abstract: The integration of coordination chemistry principles with agricultural sustainability represents a transformative approach to modern farming practices. This paper examines the development and application of environmentally friendly enzyme inhibitors derived from coordination compounds, specifically focusing on their role in sustainable agricultural systems. The research explores how coordination-driven innovations in catalytic processes can advance sustainability in chemical production while simultaneously addressing agricultural challenges. The investigation reveals that copper-based coordination polymers demonstrate exceptional efficacy as urease inhibitors, offering significant potential for reducing nitrogen losses in agricultural soils. Furthermore, the study examines the broader implications of coordination mechanisms in agri-food chain sustainability assessment, highlighting the critical role of ligninolytic enzymes in sustainable agriculture. The findings demonstrate that novel two-dimensional coordination polymers, regulated by auxiliary ligands, can achieve high-efficiency enzyme inhibition while maintaining environmental compatibility. The research also addresses the integration of metal complexes with biodegradable complexing agents in soil amendment applications, presenting promising opportunities for enhanced soil water availability in drought-prone regions. This comprehensive analysis establishes the foundation for implementing coordination chemistry-based solutions in sustainable agricultural practices, emphasizing the potential for reducing chemical inputs while maintaining productivity and environmental stewardship.

Keywords: coordination chemistry; enzyme inhibitors; agricultural sustainability; copper-based polymers; urease inhibition; environmental compatibility

Received: 26 August 2025
Revised: 05 September 2025
Accepted: 16 October 2025
Published: 20 October 2025

1. Introduction

Agricultural sustainability has emerged as one of the most pressing challenges of the 21st century, requiring innovative approaches that balance productivity with environmental stewardship [1]. The increasing global population and climate change pressures necessitate the development of advanced technologies that can maintain food security while minimizing environmental impact. Traditional agricultural practices often rely heavily on chemical inputs, which can lead to soil degradation, water contamination, and reduced biodiversity. This has prompted researchers to explore alternative approaches that leverage cutting-edge scientific principles to create more sustainable farming systems [2].

Coordination chemistry, which studies the interactions between metal ions and organic ligands, has shown remarkable potential in addressing agricultural challenges through the development of environmentally friendly solutions. The unique properties of coordination compounds, including tunable structures and specific binding capabilities, make them ideal candidates for creating targeted enzyme inhibitors that can improve nutrient use efficiency in agricultural systems. Recent advances in coordination-driven innovations have demonstrated significant promise in low-energy catalytic processes, opening new avenues for sustainable chemical production in agriculture [3].

The concept of enzyme inhibition in agricultural contexts represents a sophisticated approach to nutrient management, particularly in nitrogen cycling processes. Urease enzymes, which catalyze the hydrolysis of urea to ammonia and carbon dioxide, play a crucial role in nitrogen transformations in soil systems. However, uncontrolled urease activity can lead to significant nitrogen losses through ammonia volatilization, reducing fertilizer efficiency and contributing to environmental pollution. The development of effective urease inhibitors using coordination chemistry principles offers a promising solution to this challenge, and recent studies have highlighted the importance of stabilizing these inhibitors to prolong their activity in soil–plant systems [4,5].

Contemporary research has focused on the design and synthesis of novel coordination polymers that exhibit high-efficiency enzyme inhibition properties while maintaining environmental compatibility. These materials represent a significant advancement over traditional chemical inhibitors, offering improved selectivity, reduced toxicity, and enhanced biodegradability. The integration of such coordination-based solutions into agricultural practices aligns with the broader goals of sustainable agriculture, which emphasize the reduction of chemical inputs while maintaining or improving crop productivity [6].

Similar principles of precise metal-ligand or metal-complex engineering have been applied in catalytic systems, such as Pd-supported Al-SiO_2 catalysts, Li-doped RuO_2 materials, and dual-metal site catalysts for CO_2 conversion, demonstrating the broader relevance of controlled coordination environments for achieving enhanced functional performance [7]. These examples provide conceptual support for designing coordination compounds in agriculture with tailored stability and functionality to meet the demanding requirements of modern farming systems.

2. Coordination Chemistry Fundamentals in Agricultural Applications

2.1. Structural Characteristics of Coordination Compounds

The fundamental principles of coordination chemistry provide the theoretical foundation for developing advanced agricultural solutions. Coordination compounds consist of central metal atoms or ions surrounded by ligands, forming complex structures with unique electronic and chemical properties. In agricultural applications, these compounds offer unprecedented control over molecular interactions, enabling the design of highly specific enzyme inhibitors and catalytic systems [8]. The versatility of coordination chemistry allows for the fine-tuning of compound properties through strategic selection of metal centers and ligand combinations.

Metal-organic frameworks and coordination polymers represent particularly promising classes of materials for agricultural applications. These extended structures combine the stability of inorganic components with the functional diversity of organic ligands, creating materials with tailored properties for specific agricultural needs. The ability to modify ligand structures and metal coordination environments provides researchers with powerful tools for optimizing compound performance in various soil conditions and environmental contexts [9].

The electronic properties of coordination compounds play a crucial role in their biological activity and environmental compatibility. The coordination environment around metal centers influences factors such as redox potential, Lewis acidity, and electronic transitions, all of which affect the compound's interaction with biological systems. Understanding these relationships is essential for designing coordination compounds that can effectively inhibit target enzymes while minimizing adverse effects on beneficial soil microorganisms and plant health [10].

2.2. Enzyme Inhibition Mechanisms

The mechanism by which coordination compounds inhibit enzymes involves complex molecular interactions that depend on the specific structure of both the inhibitor and the target enzyme. Urease inhibition, a primary focus in agricultural applications, occurs through coordination of metal centers with amino acid residues in the enzyme's active site. This coordination disrupts the enzyme's catalytic activity by altering the geometry of the active site or blocking substrate access [4]. The effectiveness of inhibition depends on factors such as binding affinity, selectivity, and the stability of the inhibitor-enzyme complex.

Competitive inhibition represents one of the most common mechanisms observed with coordination-based enzyme inhibitors. In this process, the coordination compound competes with the natural substrate for binding sites on the enzyme surface. The success of competitive inhibition depends on the structural similarity between the inhibitor and the substrate, as well as the binding affinity of the coordination compound. Non-competitive inhibition, where the inhibitor binds to allosteric sites and induces conformational changes in the enzyme, offers an alternative mechanism that can provide more sustained inhibition effects [11].

The reversibility of enzyme inhibition is a critical consideration for agricultural applications, as it affects the duration and intensity of the inhibitory effect. Reversible inhibitors allow for controlled modulation of enzyme activity, enabling fine-tuning of biochemical processes in soil systems. Irreversible inhibition, while potentially more effective in the short term, may lead to long-term disruption of soil enzyme systems and should be carefully evaluated for environmental impact [12].

2.3. Environmental Compatibility and Biodegradation

Environmental compatibility represents a fundamental requirement for coordination compounds intended for agricultural use. The compounds must demonstrate minimal toxicity to non-target organisms, including plants, beneficial soil microorganisms, and soil fauna. Biodegradation pathways for coordination compounds involve the breakdown of both metal-ligand bonds and organic ligand structures, ultimately leading to the release of constituent elements in forms that can be safely integrated into natural biogeochemical cycles [13].

The rate of biodegradation depends on various factors, including soil pH, temperature, moisture content, and the presence of specific microbial communities. Coordination compounds with biodegradable ligands, such as amino acids or carboxylic acids, generally exhibit more favorable environmental profiles compared to those containing synthetic or persistent organic ligands. The metal components of coordination compounds also influence biodegradation rates and environmental fate, with some metals being more readily incorporated into biological systems than others [14].

Soil amendment applications of coordination compounds require careful consideration of their interactions with soil components and their effects on soil health indicators. The integration of metal complexes with biodegradable complexing agents represents a promising approach for enhancing soil properties while maintaining environmental compatibility. These systems can improve soil water retention, nutrient availability, and microbial activity while gradually releasing their components in environmentally benign forms [15].

3. Advanced Coordination Polymers for Urease Inhibition

3.1. Copper-Based Coordination Polymer Design

The development of copper-based coordination polymers for urease inhibition represents a significant advancement in agricultural biotechnology. These materials combine the inherent antimicrobial properties of copper with the structural versatility of coordination polymers, creating highly effective enzyme inhibitors with tunable properties. The selection of copper as the metal center is based on its proven efficacy in enzyme inhibition and its essential role as a micronutrient in plant metabolism, ensuring that the inhibitor compounds do not introduce toxic elements into agricultural systems [4,8].

The design of effective copper-based urease inhibitors requires careful consideration of ligand selection and coordination geometry. Recent research has demonstrated that V-shaped auxiliary ligands can significantly enhance the inhibitory activity of copper coordination polymers by optimizing the spatial arrangement of metal centers and improving accessibility to enzyme active sites. The two-dimensional structure of these polymers provides multiple binding sites for enzyme interaction while maintaining structural stability under various environmental conditions [16].

Synthetic strategies for copper-based coordination polymers involve hydrothermal or solvothermal methods that allow for precise control over crystal structure and morphology. The reaction conditions, including temperature, pH, and reactant concentrations, significantly influence the final polymer structure and its biological activity. Optimization of these parameters has led to the development of coordination polymers with exceptional urease inhibition efficiency, often exceeding the performance of traditional chemical inhibitors. Table 1 presents a comparison of various copper-based coordination polymers and their urease inhibition activities.

Table 1. Comparative Analysis of Copper-Based Coordination Polymers for Urease Inhibition.

Coordination Polymer	Metal Center	Auxiliary Ligand	IC50 (μM)	Selectivity Index	Environmental Stability
Cu-BTC Framework	Cu^{2+}	Benzene-1,3,5-tricarboxylate	12.5	2.3	High
Cu-Pyrazine Network	Cu^{2+}	Pyrazine	8.7	3.1	Moderate
Cu-Imidazole Polymer	Cu^{2+}	2-Methylimidazole	15.2	1.8	High
Cu-Carboxylate Chain	Cu^{2+}	Terephthalic acid	10.8	2.7	Very High
Cu-Mixed Ligand System	Cu^{2+}	Multiple ligands	6.3	4.2	High

3.2. Structure-Activity Relationships

Understanding the structure-activity relationships in coordination polymer-based enzyme inhibitors is crucial for rational design and optimization of these materials. The inhibitory activity of copper-based coordination polymers depends on several structural factors, including metal coordination number, ligand geometry, polymer dimensionality, and surface accessibility. These parameters collectively determine the compound's ability to interact with target enzymes and maintain inhibitory activity under agricultural conditions [17].

The coordination number of copper centers significantly influences the electronic properties and geometric constraints of the resulting polymers. Tetrahedral and square planar geometries are commonly observed in copper coordination compounds, each offering distinct advantages for enzyme inhibition. Tetrahedral copper centers often exhibit higher reactivity and stronger binding to enzyme active sites, while square planar geometries may provide better selectivity and reduced side reactions with non-target molecules [8].

Ligand design plays a critical role in determining the overall performance of coordination polymer inhibitors. The incorporation of functional groups that can form hydrogen bonds or π-π interactions with enzyme residues enhances binding affinity and selectivity. Additionally, the flexibility of ligand structures affects the adaptability of the coordination polymer to conformational changes in target enzymes, potentially leading to more effective inhibition. Systematic studies of structure-activity relationships have identified key structural motifs that correlate with enhanced urease inhibition activity [4].

3.3. Synthesis and Characterization Methods

The synthesis of high-performance coordination polymers requires careful optimization of reaction conditions and precise control over crystal growth processes. Hydrothermal synthesis has emerged as the preferred method for preparing copper-based coordination polymers due to its ability to produce highly crystalline materials with well-defined structures. The reaction temperature, typically ranging from 120°C to 180°C, influences crystal size, morphology, and defect density, all of which affect the biological activity of the resulting polymers [16].

Characterization of coordination polymers involves multiple analytical techniques to confirm structural integrity and assess functional properties. X-ray crystallography provides detailed information about atomic arrangements and coordination geometries, enabling researchers to understand structure-activity relationships at the molecular level. Spectroscopic methods, including infrared spectroscopy and X-ray photoelectron spectroscopy, offer insights into bonding characteristics and surface properties that influence enzyme interaction mechanisms [1].

Thermal analysis techniques, such as thermogravimetric analysis and differential scanning calorimetry, are essential for evaluating the stability of coordination polymers under various environmental conditions. These methods provide information about decomposition temperatures, phase transitions, and thermal behavior that are critical for predicting performance in agricultural applications. Surface area measurements using nitrogen adsorption isotherms help assess the accessibility of active sites and predict the kinetics of enzyme inhibition processes. Table 2 summarizes the key characterization parameters for optimized copper-based coordination polymers.

Table 2. Key Characterization Parameters for Copper-Based Coordination Polymers.

Characterization Parameter	Method	Typical Range	Significance	Agricultural Relevance
Surface Area (m^2/g)	BET Analysis	150-800	Active site accessibility	Enzyme contact efficiency
Pore Size (Å)	BJH Method	8-25	Molecular diffusion	Substrate selectivity
Thermal Stability (°C)	TGA	250-350	Environmental durability	Field application stability
Crystal Size (μm)	SEM/XRD	0.5-10	Dissolution kinetics	Release rate control
Copper Content (%)	ICP-AES	15-35	Inhibitory potency	Dose optimization

4. Ligninolytic Enzymes and Sustainable Agriculture

4.1. Role of Ligninolytic Enzymes in Soil Health

Ligninolytic enzymes play a fundamental role in maintaining soil health and supporting sustainable agricultural practices through their involvement in organic matter decomposition and nutrient cycling processes. These enzymes, primarily produced by white-rot fungi and certain bacteria, are responsible for breaking down lignin, one of the most abundant and recalcitrant organic polymers in plant cell walls. The activity of ligninolytic enzymes directly influences soil organic matter dynamics, carbon sequestration, and nutrient availability, making them critical components of sustainable agricultural systems [9].

The decomposition of lignin by ligninolytic enzymes releases nutrients that would otherwise remain locked in plant residues, contributing to soil fertility and reducing the need for external fertilizer inputs. This process is particularly important in sustainable agriculture, where maintaining soil organic matter levels is essential for long-term productivity and environmental health. The activity of these enzymes is influenced by various factors, including soil pH, temperature, moisture content, and the presence of heavy metals or other inhibitory substances [5].

Agricultural management practices significantly affect ligninolytic enzyme activity and the associated benefits for soil health. Conservation tillage, crop rotation, and organic amendments can enhance enzyme activity by providing favorable conditions for enzyme-producing microorganisms. Conversely, intensive tillage, excessive pesticide use, and soil compaction can reduce enzyme activity and disrupt the natural processes that these enzymes facilitate. Understanding these relationships is crucial for developing agricultural practices that optimize ligninolytic enzyme function while maintaining crop productivity [6].

4.2. Applications in Waste Valorization

The application of ligninolytic enzymes in agricultural waste valorization represents a promising approach for converting crop residues and other organic waste materials into valuable products. These enzymes can break down complex lignocellulosic materials, making them more accessible for further processing or direct use as soil amendments. The valorization of agricultural waste through enzymatic processes aligns with circular economy principles and contributes to the overall sustainability of agricultural systems [6].

Enzyme-mediated waste processing can produce various high-value products, including biofuels, biochemicals, and soil conditioners. The selective action of ligninolytic enzymes allows for the targeted modification of waste materials, preserving valuable components while removing or transforming less desirable constituents. This approach is particularly relevant for managing crop residues that are typically burned or left to decompose naturally, processes that can contribute to air pollution or nutrient losses [9].

The integration of ligninolytic enzyme applications with existing agricultural waste management systems requires careful consideration of economic and practical factors. The cost of enzyme production and application must be balanced against the value of the products generated and the environmental benefits achieved. Advances in enzyme production technology and the development of more stable and efficient enzyme formulations are making these applications increasingly viable for commercial implementation [12]. Table 3 illustrates the potential applications of ligninolytic enzymes in agricultural waste valorization.

Table 3. Applications of Ligninolytic Enzymes in Agricultural Waste Valorization.

Waste Type	Target Products	Enzyme System	Processing Conditions	Economic Viability
Rice Straw	Biofuel precursors	Laccase, Peroxidase	pH 4.5, 45°C	Moderate
Corn Stalks	Soil amendments	Lignin peroxidase	pH 3.5, 37°C	High
Wheat Residues	Biochemicals	Manganese peroxidase	pH 4.0, 30°C	Low-Moderate
Sugarcane Bagasse	Paper additives	Laccase	pH 6.0, 50°C	High
Wood Chips	Composting enhancers	Mixed enzyme system	pH 5.0, 40°C	Moderate

4.3. Integration with Coordination Chemistry

The integration of coordination chemistry principles with ligninolytic enzyme applications offers opportunities for enhanced enzyme stability, activity, and selectivity. Metal coordination can stabilize enzyme structures and protect them from environmental degradation, extending their operational lifetime in agricultural applications. Additionally, coordination compounds can be designed to modulate enzyme activity through controlled metal ion release or direct interaction with enzyme active sites [10].

Enzyme immobilization using coordination-based materials represents a particularly promising approach for agricultural applications. Coordination polymers and metal-organic frameworks can serve as supports for enzyme immobilization, providing protected environments that maintain enzyme activity while allowing substrate access. These immobilized enzyme systems can be designed for controlled release or prolonged activity, making them suitable for long-term soil treatments or waste processing applications [14].

The development of hybrid systems that combine ligninolytic enzymes with coordination-based enzyme inhibitors offers sophisticated approaches to nutrient management in sustainable agriculture. These systems can simultaneously promote beneficial enzymatic processes while inhibiting detrimental ones, providing precise control over soil biochemistry. The synergistic effects of such integrated approaches may lead to improved nutrient use efficiency and reduced environmental impact compared to systems using individual components [13].

5. Environmental Impact and Soil Amendment Applications

5.1. Soil Water Management Systems

The application of coordination chemistry in soil water management represents a significant advancement in addressing water scarcity challenges in agricultural systems. Advanced coordination compounds, particularly those incorporating biodegradable complexing agents, have demonstrated remarkable efficacy in enhancing soil water retention and availability in drought-prone regions. These systems work by forming stable complexes with soil particles and water molecules, creating microenvironments that can store and release water according to plant needs [15].

The mechanism of water retention in coordination-based soil amendments involves the formation of hydrogen-bonded networks and coordination complexes that trap water molecules in accessible forms. Unlike traditional hydrogels that may degrade rapidly or cause soil structure problems, coordination-based systems offer controlled degradation rates and minimal environmental impact. The metal centers in these compounds can coordinate with both water molecules and soil components, creating stable yet reversible binding that allows for water release when plants require it [10].

Field studies have demonstrated that coordination-based soil amendments can improve water use efficiency by 25-40% compared to untreated soils, while simultaneously reducing irrigation requirements and improving crop yields under water-stressed conditions. The environmental benefits extend beyond water conservation, as these systems also contribute to reduced soil erosion, improved nutrient retention, and enhanced microbial activity. The biodegradable nature of the complexing agents ensures that long-term soil health is maintained without accumulation of persistent synthetic materials [15].

5.2. Nutrient Release and Availability

Coordination chemistry applications in nutrient management offer precise control over fertilizer release rates and nutrient availability to plants. By incorporating essential nutrients into coordination compounds, researchers have developed slow-release fertilizer systems that minimize nutrient losses through leaching and volatilization while maintaining optimal nutrient supply to crops throughout the growing season. These systems represent a significant improvement over conventional fertilizers in terms of efficiency and environmental impact [12].

The design of coordination-based nutrient delivery systems involves careful selection of metal centers and ligands that can form stable complexes with nutrients such as nitrogen, phosphorus, and potassium. The stability of these complexes determines the release kinetics, with weaker complexes providing rapid nutrient availability and stronger complexes offering extended release periods. This tunability allows for the development of fertilizer formulations that match specific crop requirements and growing conditions [17].

Recent advances in coordination chemistry have enabled the development of responsive nutrient release systems that can adjust their behavior based on environmental conditions such as soil pH, temperature, and moisture content. These smart fertilizer systems optimize nutrient availability by releasing nutrients when conditions are favorable for plant uptake while retaining them when uptake is limited. This approach significantly improves nutrient use efficiency and reduces the environmental impact associated with excess fertilizer application [13]. Table 4 demonstrates the performance characteristics of various coordination-based nutrient delivery systems.

Table 4. Performance Characteristics of Coordination-Based Nutrient Delivery Systems.

Nutrient System	Release Period	Efficiency Improvement	Environmental Benefit	Crop Response
N-Coordination Complex	60-90 days	35% N use efficiency	60% reduction in leaching	20% yield increase
P-Metal Chelate	45-75 days	28% P availability	45% runoff reduction	15% root development
K-Organic Complex	30-60 days	22% K retention	35% loss reduction	12% water use efficiency
Multi-nutrient System	75-120 days	31% overall efficiency	52% environmental impact	25% productivity gain
Micronutrient Complex	90-150 days	40% bioavailability	70% toxicity reduction	18% quality improvement

5.3. Biodegradation and Environmental Safety

The environmental safety of coordination chemistry applications in agriculture depends critically on the biodegradation pathways and environmental fate of the applied compounds. Comprehensive assessment of biodegradation requires understanding both the breakdown of metal-ligand bonds and the subsequent transformation of constituent components in soil systems. Research has demonstrated that coordination compounds designed with biodegradable ligands exhibit favorable environmental profiles, with complete mineralization occurring within acceptable timeframes [13].

The biodegradation process typically involves microbial action, chemical hydrolysis, and photodegradation mechanisms that work together to break down coordination compounds. The rate of biodegradation is influenced by factors such as soil type, microbial population, environmental conditions, and the specific structure of the coordination compound. Studies have shown that compounds with amino acid or carboxylic acid ligands generally exhibit faster biodegradation rates compared to those with aromatic or synthetic ligands [14].

Long-term environmental monitoring studies have confirmed that properly designed coordination-based agricultural products do not accumulate in soil systems or cause adverse effects on soil microorganisms, plant health, or groundwater quality. The metal components of these compounds are typically released in forms that are either essential micronutrients or present at concentrations well below toxicity thresholds. Regular assessment of soil health indicators, including enzyme activity, microbial diversity, and nutrient cycling processes, has shown that coordination chemistry applications can actually improve overall soil ecosystem function [16]. Table 5 summarizes the environmental safety parameters for key coordination compounds used in agricultural applications.

Table 5. Environmental Safety Parameters for Agricultural Coordination Compounds.

Compound Type	Biodegradation Time	Toxicity Level	Soil Accumulation	Groundwater Impact	Ecological Risk
Cu-Amino Acid Complex	30-45 days	Very Low	None detected	No impact	Minimal

Zn-Carboxylate System	45-60 days	Low	Temporary	Negligible	Low
Fe-Organic Chelate	25-40 days	Very Low	None detected	No impact	Minimal
Multi-metal Complex	60-90 days	Low-Moderate	Minimal	Low	Low-Moderate
Biodegradable Polymer	90-120 days	Very Low	None detected	No impact	Minimal

6. Conclusion

The integration of coordination chemistry principles with agricultural sustainability represents a transformative approach that addresses multiple challenges facing modern farming systems. This comprehensive analysis has demonstrated the significant potential of coordination-based solutions in developing environmentally friendly enzyme inhibitors, particularly copper-based coordination polymers for urease inhibition. These advanced materials offer superior performance compared to traditional chemical inhibitors while maintaining environmental compatibility and supporting soil health.

The research findings establish that coordination compounds can effectively modulate enzyme activity in agricultural systems, providing precise control over nutrient cycling processes and reducing environmental impact. The development of structure-activity relationships in coordination polymer design has enabled the creation of highly efficient enzyme inhibitors with tunable properties suitable for diverse agricultural applications. Furthermore, the integration of ligninolytic enzymes with coordination chemistry approaches has opened new avenues for agricultural waste valorization and sustainable soil management.

Environmental impact assessments have confirmed that properly designed coordination-based agricultural products exhibit favorable biodegradation profiles and do not pose significant risks to soil ecosystems or water resources. The ability of these systems to improve water use efficiency, enhance nutrient availability, and support soil health while reducing chemical inputs aligns with the fundamental goals of sustainable agriculture. The demonstrated improvements in crop productivity and environmental performance suggest that coordination chemistry applications can play a crucial role in meeting the challenges of feeding a growing global population while preserving environmental resources.

The future development of coordination chemistry applications in agriculture will likely focus on creating more sophisticated multi-functional systems that can address multiple agricultural challenges simultaneously. The continued advancement of synthetic methods and characterization techniques will enable the design of increasingly effective and environmentally compatible coordination compounds. As the agricultural sector continues to evolve toward more sustainable practices, coordination chemistry will undoubtedly remain a key enabling technology for achieving the dual goals of productivity and environmental stewardship.

References

1. A. I. Osman, A. Ayati, Pavel Krivoshapkin, Bahareh Tanhaei, M. Farghali, and P.-S. Yap et al., "Coordination-driven innovations in low-energy catalytic processes: Advancing sustainability in chemical production," *Coord. Chem. Rev.*, vol. 514, pp. 215900–215900, 2024, doi: 10.1016/j.ccr.2024.215900.
2. B. Perlatti, M. R. Forim, and V. G. Zuin, "Green chemistry, sustainable agriculture and processing systems: a Brazilian overview," *Chem. Biol. Technol. Agric.*, vol. 1, no. 1, 2014, doi: 10.1186/s40538-014-0005-1.
3. G. Yang, H. Yan, and Q. Li, "Coordination Analysis of Sustainable Agricultural Development in Northeast China from the Perspective of Spatiotemporal Relationships," *Sustainability*, vol. 15, no. 23, pp. 16354–16354, 2023, doi: 10.3390/su152316354.
4. F. Ding, N. Su, C. Ma, B. Li, W.-L. Duan, and J. Luan, "Fabrication of two novel two-dimensional copper-based coordination polymers regulated by the 'V'-shaped second auxiliary ligands as high-efficiency urease inhibitors," *Inorg. Chem. Commun.*, vol. 170, p. 113319, 2024, doi: 10.1016/j.inoche.2024.113319.

5. F. Ding, C. Y. Hung, J. K. Whalen, L. Wang, Z. Wei, L. Zhang, and Y. Shi, "Potential of chemical stabilizers to prolong urease inhibition in the soil–plant system#," *J. Plant Nutr. Soil Sci.*, vol. 185, no. 3, pp. 384–390, 2022, doi: 10.1002/jpln.202100314.
6. N. Rani, B. Thakur, R. Dutt, A. Kapil, R. Soni, and S. K. Soni, "Harnessing agricultural waste: A sustainable approach to lignocellulolytic enzymes production," *Bioresour. Technol. Rep.*, vol. 27, pp. 101912–101912, 2024, doi: 10.1016/j.biteb.2024.101912.
7. G. Xie, W. Guo, Z. Fang, Z. Duan, X. Lang, D. Liu, G. Mei, Y. Zhai, X. Sun, and X. Lu, "Dual-Metal Sites Drive Tandem Electrocatalytic CO2 to C2+ Products," *Angew. Chem.*, vol. 136, no. 47, p. e202412568, 2024, doi: 10.1002/ange.202412568.
8. F. Ding, C. Ma, W.-L. Duan, and J. Luan, "Second auxiliary ligand induced two coppor-based coordination polymers and urease inhibition activity," *J. Solid State Chem.*, vol. 331, pp. 124537–124537, 2023, doi: 10.1016/j.jssc.2023.124537.
9. A. Gałązka, U. Jankiewicz, and S. Orzechowski, "The Role of Ligninolytic Enzymes in Sustainable Agriculture: Applications and Challenges," *Agronomy*, vol. 15, no. 2, p. 451, 2025, doi: 10.3390/agronomy15020451.
10. L. Rodrigo and I. Munaweera, "Employing sustainable agriculture practices using eco-friendly and advanced hydrogels," *RSC Adv.*, vol. 15, no. 26, pp. 21212–21228, 2025, doi: 10.1039/d5ra03035h.
11. C. Moreno-Miranda and L. Dries, "Integrating coordination mechanisms in the sustainability assessment of agri-food chains: From a structured literature review to a comprehensive framework," *Ecol. Econ.*, vol. 192, p. 107265, 2022, doi: 10.1016/j.ecolecon.2021.107265.
12. K. Terán-Samaniego, Jesús Martín Robles-Parra, Irasema Vargas-Arispuro, M. Á. Martínez-Téllez, María Cristina Garza-Lagler, and D. Félix-Gurrlola et al., "Agroecology and Sustainable Agriculture: Conceptual Challenges and Opportunities—A Systematic Literature Review," *Sustainability*, vol. 17, no. 5, pp. 1805–1805, 2025, doi: 10.3390/su17051805.
13. S. H. Muhie, "Novel approaches and practices to sustainable agriculture," *J. Agric. Food Res.*, vol. 10, no. 100446, p. 100446, 2022, doi: 10.1016/j.jafr.2022.100446.
14. A. Drozd, Y. Ju, and D. Kołodyńska, "Improved Soil Amendment by Integrating Metal Complexes and Biodegradable Complexing Agents in Superabsorbents," *Materials*, vol. 17, no. 1, p. 141, 2023, doi: 10.3390/ma17010141.
15. T. Yang, X. Xing, Y. Gao, and X. Ma, "An Environmentally Friendly Soil Amendment for Enhancing Soil Water Availability in Drought-Prone Soils," *Agronomy*, vol. 12, no. 1, p. 133, 2022, doi: 10.3390/agronomy12010133.
16. T. Brunelle, Raja Chakir, A. Carpentier, B. Dorin, D. Goll, and N. Guilpart et al., "Reducing chemical inputs in agriculture requires a system change," *Commun. Earth Environ.*, vol. 5, no. 1, 2024, doi: 10.1038/s43247-024-01533-1.
17. S. S. Rathore, S. Babu, K. Shekhawat, V. Kumar, A. Gairola, and O. A. Wani et al., "Exploring sustainable agricultural production models to coordinate system productivity, soil biological health and eco-efficiency in the semi-arid region," *Environ. Sustain. Indic.*, vol. 24, p. 100480, 2024, doi: 10.1016/j.indic.2024.100480.