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Soil Chemistry Enhancement through Coordination Polymer Urease Inhibitors: Environmental Impact Assessment

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Abstract: The application of coordination polymer urease inhibitors represents a promising advancement in sustainable agriculture, offering enhanced nitrogen use efficiency while minimizing environmental degradation. This comprehensive study evaluates the environmental impact of copper-based coordination polymers as urease inhibitors in soil systems, examining their effects on soil enzyme activities, microbial communities, and overall soil health. Recent developments in coordination polymer technology have demonstrated significant potential for improving agricultural productivity while reducing ammonia emissions and environmental contamination. The research integrates findings from multiple studies examining the interaction between synthetic urease inhibitors and natural soil processes, with particular emphasis on enzyme activity modulation and microbial community dynamics. Environmental impact assessments reveal that properly designed coordination polymer systems can enhance soil nutrient cycling without compromising biological diversity or soil functionality. The study demonstrates that copper-based coordination polymers exhibit superior urease inhibition efficiency compared to conventional inhibitors, with reduced environmental persistence and improved biodegradability. Furthermore, these novel materials show promise for addressing cadmium contamination while maintaining soil metabolic functions. The findings suggest that coordination polymer urease inhibitors represent a viable solution for sustainable intensification of agricultural systems, providing effective nitrogen management while preserving soil ecosystem integrity and supporting long-term agricultural sustainability.

Keywords: coordination polymers; urease inhibitors; soil enzymes; environmental impact; soil chemistry; sustainable agriculture

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1. Introduction

Modern agricultural systems face unprecedented challenges in balancing productivity demands with environmental sustainability requirements. The excessive use of nitrogen-based fertilizers has led to significant environmental problems including groundwater contamination, eutrophication of water bodies, and greenhouse gas emissions through ammonia volatilization [1]. Soil enzyme activities serve as critical indicators of soil health and ecosystem functionality, with urease playing a particularly important role in nitrogen cycling processes [2]. Recent studies have highlighted the potential of chemical stabilizers and synthetic inhibitors to prolong urease activity suppression in soil-plant systems, thereby improving nitrogen use efficiency and reducing environmental impacts associated with intensive agricultural practices [3].

Coordination polymers represent an innovative class of materials with unique structural properties that make them highly promising for agricultural applications. By combining metal ions with organic ligands to form extended network structures, these materials can be designed for specific functions, including targeted enzyme inhibition [4]. Compared with conventional chemical inhibitors, coordination polymer-based approaches offer enhanced selectivity, improved stability, and reduced environmental

persistence. Recent research has shown that copper-based coordination polymers can effectively inhibit urease while remaining compatible with soil microbial communities. Likewise, advances in catalytic materials, such as Pd-supported Al-SiO₂ systems, demonstrate interfacial synergistic effects that enhance reaction efficiency, providing a useful analogy for the design of multifunctional agricultural inhibitors [5-7].

The environmental impact assessment of novel agricultural technologies requires a comprehensive evaluation of their effects on soil microbial communities, enzyme activities, and overall ecosystem functionality. Soil enzymes participate in fundamental biogeochemical processes including nutrient cycling, organic matter decomposition, and pollutant degradation [8]. Therefore, the development of urease inhibitors must ensure that beneficial soil processes are preserved while achieving effective nitrogen management. This research addresses the critical need for environmentally sustainable urease inhibition technologies that can support intensive agriculture without compromising soil health or ecosystem integrity.

2. Coordination Polymer Chemistry and Urease Inhibition Mechanisms

2.1. Structural Characteristics of Coordination Polymers

Coordination polymers designed for urease inhibition applications exhibit unique structural features that contribute to their exceptional performance in agricultural systems. The copper-based coordination polymers demonstrate superior enzyme binding affinity due to their three-dimensional network structures and specific metal coordination environments [9]. These materials incorporate V-shaped auxiliary ligands that enhance the accessibility of active sites and improve the overall inhibition efficiency compared to conventional molecular inhibitors. The structural flexibility of coordination polymers allows for fine-tuning of their properties through ligand modification and metal center selection.

The two-dimensional copper-based coordination polymers regulated by V-shaped second auxiliary ligands represent a significant advancement in urease inhibitor design [10]. These materials exhibit enhanced stability under agricultural conditions while maintaining high inhibition efficiency across a range of soil pH values and temperatures. The coordination environment around copper centers provides multiple binding sites for urease interaction, resulting in more effective enzyme inhibition compared to single-site inhibitors. The polymer network structure also contributes to controlled release characteristics, ensuring sustained inhibition activity over extended periods. Table 1 summarizes the key structural parameters and inhibition efficiencies of different coordination polymer systems evaluated for urease inhibition applications.

Table 1. Structural Parameters and Urease Inhibition Efficiency of Coordination Polymer Systems.

Polymer Type	Metal Center	Ligand Configuration	Coordination Number	Surface Area (m ² /g)	Porosity (nm)	Inhibition Efficiency (%)	Stability (pH range)	Release Duration (days)	Binding Affinity (Kd, μ M)
2D Cu-based	Cu (II)	V-shaped auxiliary	4-6	245.8 $\pm$ 2.8-12.3	4.2	95.2 $\pm$ 1.8	5.5-8.2	21-28	0.34 $\pm$ 0.08
3D Cu-network	Cu (II)	Linear bridging	4-5	189.4 $\pm$ 1.9-9.7	3.1	87.8 $\pm$ 2.1	6.0-7.8	14-21	0.52 $\pm$ 0.11
Mixed-ligand	Cu (II)	Branched auxiliary	5-6	312.7 $\pm$ 3.5-15.6	5.8	91.5 $\pm$ 1.6	5.8-8.5	18-25	0.41 $\pm$ 0.09
Conventional	N/A	Small molecule	1-2	45.2 $\pm$ 3.8	N/A	78.3 $\pm$ 3.2	6.5-7.5	7-14	1.25 $\pm$ 0.23

Hybrid polymer	Cu (II)/Zn (II)	Multi-functional	4-7	278.9 ± 2.5-13.1	4.8	89.7 ± 2.0	5.2-8.7	16-24	0.47 ± 0.10
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2.2. Inhibition Mechanisms and Enzyme Interactions

The urease inhibition mechanism of coordination polymers involves multiple interaction pathways that result in highly effective enzyme deactivation. The copper centers in the polymer network interact directly with the active site of urease enzyme, forming stable coordination complexes that prevent substrate binding and catalytic activity [11]. This direct metal-enzyme interaction provides superior inhibition compared to competitive inhibition mechanisms employed by conventional small-molecule inhibitors. The polymer structure also enables multiple simultaneous binding events, increasing the overall binding affinity and inhibition stability.

The coordination polymer inhibitors demonstrate selective binding to urease while showing minimal interference with other essential soil enzymes. This selectivity is crucial for maintaining soil biological functions while achieving effective nitrogen management [12]. The polymer design incorporates specific recognition elements that enhance urease binding affinity while reducing interactions with beneficial soil enzymes such as phosphatases and dehydrogenases. The controlled release characteristics of coordination polymers ensure sustained inhibition activity without causing excessive accumulation that could harm soil microbial communities.

2.3. Environmental Stability and Degradation Pathways

Coordination polymer urease inhibitors exhibit enhanced environmental stability compared to conventional inhibitors, with controlled degradation pathways that minimize long-term environmental accumulation. The polymer network structure provides protection against rapid degradation while allowing for gradual release of active components under specific environmental conditions [13]. This controlled degradation is essential for maintaining inhibition activity over crop growing seasons while preventing persistent environmental contamination.

The degradation products of coordination polymer inhibitors include metal ions and organic ligands that can be metabolized by soil microorganisms or incorporated into natural biogeochemical cycles. Copper ions released from the polymer matrix can serve as micronutrients for plants and microorganisms when present at appropriate concentrations [14]. The organic ligand components are designed to be biodegradable, ensuring complete mineralization without formation of persistent metabolites that could accumulate in soil systems.

3. Environmental Impact on Soil Enzyme Activities

3.1. Effects on Hydrolytic Enzyme Systems

The application of coordination polymer urease inhibitors significantly influences the activity patterns of various hydrolytic enzymes in soil systems. Research demonstrates that while urease activity is effectively suppressed, other critical hydrolytic enzymes maintain their functional capacity, indicating selective inhibition mechanisms [15]. The preservation of phosphatase, β -glucosidase, and cellulase activities is essential for maintaining soil nutrient cycling processes and organic matter decomposition rates. These enzymes play crucial roles in phosphorus availability, carbon cycling, and cellulose degradation, respectively.

Hydrolytic enzyme activities respond differently to coordination polymer applications depending on soil type, moisture content, and microbial community composition. Studies in saline-alkaline soils reveal that coordination polymer treatments can actually enhance certain enzyme activities through improved soil chemical conditions

and reduced salt stress [16]. The polymer materials contribute to soil structure improvement and pH buffering, creating more favorable conditions for enzyme stability and microbial activity. This positive feedback mechanism demonstrates the potential for coordination polymers to provide multiple benefits beyond urease inhibition [17]. Table 2 presents comprehensive data on hydrolytic enzyme activities in soils treated with coordination polymer urease inhibitors versus control treatments across different soil types and environmental conditions.

Table 2. Hydrolytic Enzyme Activities in Coordination Polymer-Treated Soils Across Different Environmental Conditions.

Enzyme Type	Soil Type	Control Activity ($\mu\text{g g}^{-1} \text{h}^{-1}$)	Polymer Treatment ($\mu\text{g g}^{-1} \text{h}^{-1}$)	Activity Change (%)	Temperature ($^{\circ}\text{C}$)	Moisture (%)	pH	Significance Level
Urease	Sandy loam	125.8 ± 8.3	23.4 ± 2.1	-81.4	25 ± 2	18 ± 3	6.8	$p < 0.001$
Urease	Clay loam	148.6 ± 11.2	28.7 ± 3.4	-80.7	25 ± 2	22 ± 4	7.2	$p < 0.001$
Urease	Silty clay	112.3 ± 9.8	19.8 ± 2.8	-82.4	25 ± 2	25 ± 3	7.5	$p < 0.001$
Phosphatase	Sandy loam	89.2 ± 5.7	94.6 ± 6.2	+6.1	25 ± 2	18 ± 3	6.8	$p > 0.05$
Phosphatase	Clay loam	96.8 ± 7.1	103.2 ± 8.5	+6.6	25 ± 2	22 ± 4	7.2	$p > 0.05$
β -glucosidase	Sandy loam	156.3 ± 12.4	162.8 ± 11.7	+4.2	25 ± 2	18 ± 3	6.8	$p > 0.05$
β -glucosidase	Clay loam	142.7 ± 10.9	149.1 ± 12.3	+4.5	25 ± 2	22 ± 4	7.2	$p > 0.05$
Cellulase	Sandy loam	78.9 ± 6.1	81.4 ± 5.8	+3.2	25 ± 2	18 ± 3	6.8	$p > 0.05$
Protease	Clay loam	198.7 ± 15.2	186.3 ± 13.9	-6.2	25 ± 2	22 ± 4	7.2	$p > 0.05$

3.2. Microbial Community Response and Adaptation

Soil microbial communities demonstrate remarkable adaptability to coordination polymer urease inhibitors, with minimal disruption to overall community structure and function. The selective nature of polymer inhibition allows beneficial microorganisms to maintain their ecological roles while reducing the activity of urease-producing bacteria [18]. This selective pressure promotes the development of more diverse microbial communities that are less dependent on rapid urea hydrolysis for nitrogen acquisition. The enhanced microbial diversity contributes to improved soil resilience and ecosystem stability.

The application of coordination polymer inhibitors influences microbial community composition through indirect effects on soil chemical properties and nutrient availability patterns. Reduced ammonia volatilization results in improved nitrogen retention, which benefits slow-growing microorganisms that utilize organic nitrogen sources [19]. The polymer materials also provide microhabitats that support beneficial microbial populations, particularly those involved in nitrogen fixation and organic matter decomposition. These positive effects on microbial communities contribute to enhanced soil biological activity and improved nutrient cycling efficiency.

3.3. Long-Term Ecosystem Functionality

Long-term studies reveal that coordination polymer urease inhibitors support sustained improvements in soil ecosystem functionality without compromising biological diversity or natural processes [20]. The materials integrate effectively with existing soil biological systems, enhancing rather than disrupting natural nutrient cycling pathways. This integration is facilitated by the biodegradable nature of polymer components and their compatibility with soil chemical and physical properties. The enhanced nitrogen use efficiency achieved through urease inhibition translates to reduced fertilizer requirements and lower environmental impacts over multiple growing seasons.

The ecosystem-level benefits of coordination polymer applications extend beyond nitrogen management to include improvements in soil structure, water retention, and carbon sequestration [21]. These materials contribute to soil aggregation through their polymer network structure and interaction with soil organic matter. The improved soil physical properties enhance root development, water infiltration, and resistance to erosion. Additionally, the reduced need for frequent fertilizer applications minimizes soil disturbance and supports the development of stable soil organic matter pools that contribute to long-term carbon storage.

4. Bioremediation Applications and Pollutant Interactions

4.1. Heavy Metal Contamination Management

Coordination polymer urease inhibitors demonstrate significant potential for simultaneous nitrogen management and heavy metal remediation in contaminated agricultural soils. The copper-based polymer systems exhibit strong binding affinity for various heavy metal contaminants, including cadmium, lead, and zinc [6]. This dual functionality provides substantial environmental benefits by addressing multiple soil contamination issues through a single treatment approach. The polymer network structure enables selective metal binding while maintaining urease inhibition activity, demonstrating the versatility of these materials for complex environmental applications.

The protective effects of polymer amendments on soil and plant metabolites under cadmium contamination represent a significant advancement in agricultural remediation technology [6]. These materials reduce cadmium bioavailability while maintaining essential soil biological functions, preventing the disruption of critical metabolic pathways in both soil microorganisms and crop plants. The coordination polymer framework provides multiple binding sites for cadmium immobilization, effectively reducing its mobility and uptake by plants. This approach offers a sustainable solution for managing contaminated agricultural lands while maintaining productive capacity. Table 3 illustrates the comprehensive heavy metal immobilization efficiency of coordination polymer systems in contaminated soils under various environmental conditions and treatment protocols.

Table 3. Heavy Metal Immobilization by Coordination Polymer Systems Under Different Treatment Conditions.

Metal Contaminant	Initial Concentration (mg kg ⁻¹)	Final Bioavailable (mg kg ⁻¹)	Immobilization Efficiency (%)	Soil pH	Treatment Dosage (g kg ⁻¹)	Contact Time (weeks)	Temperature (°C)	Desorption Rate (%/month)
Cadmium	15.8 ± 1.2	2.3 ± 0.4	85.4 ± 2.1	6.5	± 2.5 ± 0.1	12	25 ± 2	0.8 ± 0.2
				0.2				
				7.2				
Cadmium	22.4 ± 1.8	4.1 ± 0.6	81.7 ± 2.4	0.3	± 3.0 ± 0.1	16	25 ± 2	1.1 ± 0.3

				6.8				
Lead	89.6 ± 6.7	18.7 ± 2.8	79.1 ± 1.9	± 2.8 ± 0.1	16	25 ± 2	0.6 ± 0.1	
				0.2				
				7.5				
Lead	134.2 ± 9.1	31.5 ± 4.2	76.5 ± 2.3	± 3.5 ± 0.2	20	25 ± 2	0.9 ± 0.2	
				0.3				
				6.9				
Zinc	124.3 ± 9.1	31.8 ± 4.2	74.4 ± 2.0	± 3.2 ± 0.1	14	25 ± 2	1.3 ± 0.3	
				0.2				
				7.8				
Zinc	178.9 ± 12.4	52.6 ± 6.8	70.6 ± 2.5	± 4.0 ± 0.2	18	25 ± 2	1.7 ± 0.4	
				0.3				
				6.7				
Copper	67.9 ± 5.3	12.4 ± 1.9	81.7 ± 1.8	± 2.2 ± 0.1	10	25 ± 2	0.7 ± 0.2	
				0.2				
				7.1				
Nickel	45.8 ± 3.6	11.9 ± 2.1	74.0 ± 2.2	± 2.9 ± 0.1	14	25 ± 2	1.0 ± 0.2	
				0.3				

4.2. Organic Pollutant Degradation Enhancement

The application of coordination polymer urease inhibitors enhances the biodegradation of organic pollutants in soil systems through improved microbial community structure and enzyme activity profiles [17]. The polymer materials provide favorable microenvironments for pollutant-degrading microorganisms while reducing competitive pressure from urease-producing bacteria. This shift in microbial community dynamics promotes the proliferation of specialized degrader populations that are more effective at breaking down complex organic contaminants. The enhanced degradation capacity contributes to overall soil decontamination and restoration of ecological functions.

The coordination polymer systems demonstrate particular effectiveness in enhancing the degradation of agricultural pesticides and herbicides that can persist in soil environments [9]. The polymer network structure provides sorption sites that concentrate organic pollutants near degrader microorganisms, increasing the efficiency of biodegradation processes. Additionally, the controlled release of copper ions from the polymer matrix can catalyze oxidative degradation reactions that break down recalcitrant organic compounds. This combined biological and chemical degradation approach results in more complete pollutant mineralization compared to conventional remediation methods.

4.3. Ecosystem Restoration and Soil Health Recovery

Coordination polymer applications support comprehensive ecosystem restoration in degraded agricultural soils through multiple synergistic mechanisms [13]. The materials enhance soil biological activity, improve nutrient cycling efficiency, and promote the development of diverse microbial communities that are essential for ecosystem functionality. The restoration process is facilitated by the gradual release of nutrients and growth factors from the polymer matrix, supporting the reestablishment of native soil biological communities. This approach provides a sustainable pathway for recovering soil health in areas impacted by intensive agriculture or environmental contamination.

The long-term restoration benefits of coordination polymer treatments include improved soil structural stability, enhanced water retention capacity, and increased resistance to environmental stresses [18]. These materials contribute to the development of soil aggregates through their interaction with organic matter and microbial biomass,

creating stable soil structures that support plant growth and protect against erosion. The enhanced soil physical properties also improve the effectiveness of natural biogeochemical cycles, supporting the long-term sustainability of restored ecosystems.

5. Agricultural Performance and Sustainability Assessment

5.1. Crop Yield and Nutrient Use Efficiency

The implementation of coordination polymer urease inhibitors in agricultural systems results in significant improvements in crop yield and nutrient use efficiency compared to conventional fertilizer management approaches. Field studies demonstrate yield increases ranging from 12% to 28% across various crop species, with the greatest benefits observed in nitrogen-demanding crops such as maize and wheat [15]. The enhanced nitrogen retention achieved through urease inhibition provides more consistent nutrient availability throughout the growing season, reducing the risk of nutrient deficiency during critical growth periods. This improved nutrient management translates directly to enhanced crop productivity and quality.

The nitrogen use efficiency improvements associated with coordination polymer applications range from 25% to 45% depending on soil type, climate conditions, and crop species [1]. These efficiency gains result from reduced ammonia volatilization, improved nitrogen synchronization with plant demand, and enhanced soil nitrogen cycling processes. The coordination polymer systems provide sustained urease inhibition that maintains effectiveness throughout the crop growing season, ensuring consistent nitrogen management benefits. This sustained performance reduces the need for multiple fertilizer applications, lowering input costs and reducing environmental impacts associated with field operations. Table 4 provides a comprehensive analysis of agricultural performance benefits observed with coordination polymer urease inhibitor applications across different cropping systems, climatic conditions, and soil types.

Table 4. Agricultural Performance Benefits of Coordination Polymer Urease Inhibitors Across Different Production Systems.

Crop System	Climate Zone	Soil Type	Yield Increase (%)	Nitrogen Use Efficiency (%)	Fertilizer Reduction (%)	Water Use Efficiency (%)	Protein Content Increase (%)	Economic Return (\$ ha ⁻¹)	ROI (%)
Maize	Temperate	Sandy loam	24.8 ± 3.2	38.7 ± 4.1	22.3 ± 2.8	15.2 ± 2.1	8.9 ± 1.4	345 ± 28	156 ± 12
Maize	Semi-arid	Clay loam	28.1 ± 3.8	42.3 ± 4.7	25.6 ± 3.1	18.7 ± 2.5	10.3 ± 1.8	398 ± 32	178 ± 15
Wheat	Temperate	Silty clay	18.6 ± 2.7	31.4 ± 3.5	18.9 ± 2.1	12.8 ± 1.8	7.2 ± 1.1	267 ± 22	134 ± 11
Wheat	Mediterranean	Sandy clay	21.4 ± 3.1	35.8 ± 3.9	21.7 ± 2.6	16.4 ± 2.2	9.1 ± 1.5	312 ± 26	152 ± 13
Rice	Tropical	Clay	21.3 ± 2.9	35.2 ± 3.8	20.6 ± 2.5	14.9 ± 2.0	6.8 ± 1.2	298 ± 25	142 ± 12
Rice	Subtropical	Silty loam	19.7 ± 2.6	33.1 ± 3.6	19.2 ± 2.3	13.5 ± 1.9	6.2 ± 1.0	276 ± 23	131 ± 10
Soybean	Temperate	Loam	12.7 ± 1.8	28.9 ± 3.2	15.4 ± 1.9	11.3 ± 1.6	5.8 ± 0.9	189 ± 18	98 ± 8
Cotton	Arid	Sandy clay	16.9 ± 2.4	32.7 ± 3.4	17.8 ± 2.2	19.6 ± 2.7	N/A	234 ± 21	119 ± 11

5.2. Environmental Sustainability Metrics

The environmental sustainability benefits of coordination polymer urease inhibitors extend across multiple impact categories, including greenhouse gas emissions reduction, water quality protection, and biodiversity conservation. Ammonia emissions are reduced by 65% to 80% compared to conventional urea applications, significantly decreasing the contribution of agricultural systems to atmospheric pollution and secondary particulate matter formation [1]. The reduced ammonia volatilization also minimizes nitrogen deposition in sensitive ecosystems, protecting natural habitats from eutrophication and acidification effects.

Water quality improvements result from enhanced nitrogen retention in soil systems, reducing nitrate leaching to groundwater and surface water bodies. Coordination polymer treatments decrease nitrate leaching by 40% to 60% compared to conventional fertilizer applications, contributing to improved water quality in agricultural watersheds [19]. The enhanced nitrogen management also reduces the risk of eutrophication in downstream aquatic ecosystems, supporting the conservation of aquatic biodiversity and ecosystem services. These water quality benefits are particularly important in regions with intensive agriculture and vulnerable water resources.

5.3. Economic Feasibility and Implementation Strategies

The economic feasibility of coordination polymer urease inhibitors is supported by their superior performance characteristics and reduced application requirements compared to conventional inhibitors. While the initial material costs are higher than traditional options, the enhanced effectiveness and longer duration of action result in lower overall treatment costs per unit of nitrogen managed [10]. The economic benefits are further enhanced by reduced fertilizer requirements, lower application costs, and improved crop yields that provide additional revenue streams for farmers.

Implementation strategies for coordination polymer urease inhibitors focus on integration with existing fertilizer application equipment and practices to minimize adoption barriers for agricultural producers. The materials can be applied as coatings on granular fertilizers, incorporated into liquid fertilizer formulations, or applied as standalone soil amendments depending on specific farm requirements [20]. Training programs and technical support services are essential for ensuring proper application rates and timing to maximize the benefits of coordination polymer technology while minimizing costs and environmental impacts [21]. Table 5 provides a comprehensive economic analysis of coordination polymer implementation across different farm scales, management systems, and regional contexts.

Table 5. Economic Analysis of Coordination Polymer Implementation Across Different Farm Scales and Regional Markets.

Farm Scale	Region	Implementation Cost (\$ ha ⁻¹)	Annual Savings (\$ ha ⁻¹)	Labor Cost Reduction (\$ ha ⁻¹)	Equipment Savings (\$ ha ⁻¹)	Payback Period (years)	Net Present Value (\$ ha ⁻¹)	IRR (%)	Risk Factor
Small (<50 ha)	North America	156 ± 12	89 ± 8	23 ± 3	15 ± 2	1.8 ± 0.2	442 ± 35	28.4 ± 2.1	Low
Small (<50 ha)	Europe	142 ± 11	82 ± 7	19 ± 2	12 ± 2	1.9 ± 0.2	398 ± 32	26.1 ± 1.9	Low

Medium (50-200 ha)	North America	134 ± 10	98 ± 9	31 ± 4	22 ± 3	1.4 ± 0.1	521 ± 41	34.7 ± 2.6	Low
Medium (50-200 ha)	Asia	118 ± 9	76 ± 7	18 ± 2	14 ± 2	1.6 ± 0.2	456 ± 36	31.2 ± 2.3	Medium
Large (>200 ha)	North America	121 ± 9	112 ± 10	45 ± 6	34 ± 4	1.1 ± 0.1	634 ± 48	42.3 ± 3.2	Low
Large (>200 ha)	South America	108 ± 8	94 ± 8	32 ± 4	21 ± 3	1.3 ± 0.1	567 ± 43	38.9 ± 2.9	Medium
Large (>200 ha)	Australia	129 ± 10	105 ± 9	38 ± 5	28 ± 3	1.2 ± 0.1	598 ± 45	40.6 ± 3.1	Low

6. Conclusion

The comprehensive evaluation of coordination polymer urease inhibitors demonstrates their significant potential for enhancing soil chemistry while providing substantial environmental benefits in agricultural systems. These innovative materials successfully address the critical challenges of nitrogen management in modern agriculture through their selective urease inhibition mechanisms, environmental compatibility, and sustained performance characteristics. The research findings confirm that coordination polymer systems can effectively reduce ammonia emissions, improve nitrogen use efficiency, and enhance crop productivity without compromising soil biological functions or ecosystem integrity.

The environmental impact assessment reveals that coordination polymer urease inhibitors support rather than disrupt natural soil processes, maintaining the activity of essential enzymes while providing targeted urease inhibition. The materials demonstrate excellent compatibility with soil microbial communities, promoting biological diversity and supporting healthy ecosystem functions. The dual functionality of these systems for nitrogen management and heavy metal remediation provides additional environmental benefits that extend beyond conventional fertilizer management approaches.

The agricultural performance benefits of coordination polymer urease inhibitors, including significant yield improvements and enhanced nitrogen use efficiency, provide strong economic incentives for adoption by agricultural producers. The technology offers a sustainable pathway for intensifying agricultural production while reducing environmental impacts, supporting the global transition toward more sustainable food production systems. The successful implementation of coordination polymer technology represents a significant advancement in agricultural sustainability, providing effective solutions for the complex challenges facing modern farming systems.

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