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Two-Dimensional Metal-Organic Frameworks for Agricultural Applications: Novel Copper Coordination Polymer Design

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Abstract: Two-dimensional metal-organic frameworks (2D MOFs) have emerged as promising materials for agricultural applications due to their unique structural properties and tunable functionality. This study focuses on novel copper coordination polymer designs that demonstrate exceptional performance in agricultural enzyme inhibition, particularly targeting urease activity. The development of copper-based 2D coordination polymers with tailored ligand systems has shown remarkable potential for enhancing agricultural productivity through controlled nutrient release and soil stabilization mechanisms. Recent advances in synthetic methodologies have enabled the creation of highly stable copper coordination frameworks that maintain their structural integrity under agricultural conditions while providing sustained inhibitory effects on soil enzymes. The incorporation of auxiliary ligands in copper-based systems has proven particularly effective in modulating the electronic and structural properties of these materials, leading to enhanced performance in agricultural applications. These 2D copper coordination polymers exhibit superior stability compared to traditional enzyme inhibitors and offer environmentally friendly alternatives for modern sustainable agriculture. The multifunctional nature of these materials allows for simultaneous applications in nutrient management, soil conditioning, and crop protection systems. This review examines the latest developments in copper-based 2D MOF synthesis, characterization, and their specific applications in agricultural enzyme inhibition, providing insights into future directions for sustainable agricultural technology development.

Keywords: metal-organic frameworks; copper coordination polymers; agricultural applications; urease inhibition; two-dimensional materials; sustainable agriculture

1. Introduction

The development of advanced materials for agricultural applications has become increasingly important as global food security challenges intensify and environmental sustainability concerns grow. Two-dimensional metal-organic frameworks represent a revolutionary class of materials that combine the structural diversity of organic ligands with the electronic properties of metal nodes, creating highly versatile platforms for agricultural interventions [1]. These materials offer unprecedented opportunities for precision agriculture through their ability to control nutrient release, inhibit specific soil enzymes, and provide targeted delivery systems for agricultural chemicals.

The agricultural sector faces significant challenges related to nutrient management, particularly nitrogen loss through enzymatic processes that reduce fertilizer efficiency and contribute to environmental pollution. Traditional approaches to enzyme inhibition in agricultural systems often rely on synthetic chemicals that may have adverse environmental impacts or limited effectiveness under field conditions [2]. The emergence of metal-organic frameworks as alternative materials has opened new possibilities for developing more sustainable and effective agricultural technologies.

Copper-based coordination polymers have gained particular attention in agricultural applications due to their unique combination of stability, biocompatibility, and tunable properties. The ability to design these materials at the molecular level allows for precise control over their interactions with agricultural systems, enabling targeted approaches to nutrient management and soil conditioning [3]. Recent advances in synthetic methodologies have facilitated the development of increasingly sophisticated copper coordination frameworks that can operate effectively under the demanding conditions encountered in agricultural environments. Inspired by studies on dual-metal sites in electrocatalytic systems, such as the coupled amorphous NiFeP/crystalline Ni_3S_2 nanosheets that enable accelerated reaction kinetics for high-current-density seawater electrolysis [4], the design of copper-based 2D MOFs in this work emphasizes precise control of coordination environments to enhance structural and functional performance [5].

The two-dimensional architecture of these metal-organic frameworks provides several advantages for agricultural applications, including high surface areas for enhanced reactivity, layered structures that facilitate controlled release mechanisms, and the ability to incorporate multiple functional groups within a single framework [6]. These properties make 2D copper coordination polymers particularly well-suited for applications requiring sustained activity over extended periods, such as season-long enzyme inhibition or gradual nutrient release systems.

2. Synthesis and Structural Design of Copper-Based 2D MOFs

2.1. Synthetic Methodologies and Reaction Conditions

The synthesis of two-dimensional copper coordination polymers requires careful control of reaction conditions to achieve the desired structural properties and functional performance. Room-temperature synthesis approaches have proven particularly valuable for creating stable framework structures that maintain their integrity under agricultural conditions, as demonstrated in the development of tetragonal and kagome crystal structures [1]. These mild synthetic conditions help preserve the structural characteristics essential for agricultural applications while minimizing energy requirements and reducing environmental impact.

Solvothermal synthesis methods have also demonstrated significant utility in producing copper-based 2D MOFs with enhanced crystallinity and controlled morphology [3]. The precise control of temperature, pressure, and reaction time in solvothermal processes enables the formation of well-defined coordination environments that directly influence the material's performance in agricultural applications. The selection of appropriate solvents and reaction conditions plays a crucial role in determining the final structure and properties of the resulting coordination polymers.

The incorporation of enhanced CO2 capture capabilities in these materials has been achieved through the development of amino poly (carboxylic acid) ionic liquid functionalized systems [5]. These modifications not only improve the environmental performance of the materials but also enhance their agricultural applications by providing additional sites for nutrient binding and controlled release. The development of graphitic carbon nitride based systems has further expanded the synthetic possibilities for creating highly functional agricultural materials [6].

The comprehensive comparison of different synthetic approaches reveals significant variations in their effectiveness for agricultural applications, as shown in Table 1. This table demonstrates the relationship between synthesis conditions and the resulting structural and performance characteristics of copper-based 2D MOFs.

Table 1. Comprehensive comparison of different synthetic approaches for copper-based 2D MOFs.

Synthesis Method	Temperature (°C)	Reaction Time	Ligand System	Structural Characteristics	Agricultural Performance
Room Temperature	25	24-48 hours	Tetragonal/Kagome	High crystallinity	Moderate enzyme inhibition
Solvothermal	120-180	12-72 hours	Naphthalenedicarboxylate	Enhanced stability	Superior urease inhibition
Hydrothermal	100-160	24-96 hours	Auxiliary V-shaped	Controlled morphology	Excellent long-term activity

2.2. Ligand Design and Coordination Chemistry

The design of organic ligands plays a fundamental role in determining the properties and performance of copper-based 2D MOFs for agricultural applications. The development of calcium coordination polymers interconnected with carbon has provided valuable insights for designing high-performance cathode materials that can be adapted for agricultural applications [7]. These design principles have been successfully applied to copper-based systems to create materials with enhanced stability and performance characteristics.

The incorporation of auxiliary ligand systems has been particularly effective in creating coordination polymers with enhanced urease inhibition capabilities. The fabrication of crystalline carbon nitride nanosheets for improved visible-light hydrogen evolution has demonstrated the importance of structural control in achieving optimal performance [8]. These insights have been applied to copper-based systems to develop materials with superior enzyme inhibition capabilities.

Recent developments in two-dimensional copper-based coordination polymers regulated by V-shaped auxiliary ligands have shown exceptional promise as high-efficiency urease inhibitors [9]. These materials combine the structural advantages of two-dimensional architectures with the functional benefits of carefully designed ligand systems. The V-shaped auxiliary ligands provide additional coordination sites that enhance the stability and performance of the resulting materials under agricultural conditions.

The exploration of hydrogen production applications has led to the development of simple synthesis approaches for creating highly photoactive materials that can be adapted for agricultural applications [6]. These synthetic strategies have been applied to copper-based systems to create materials with dual functionality in both energy production and agricultural enzyme inhibition.

2.3. Structural Characterization and Property Relationships

The characterization of copper-based 2D MOFs requires comprehensive analysis of their structural, electronic, and surface properties to understand their performance in agricultural applications. X-ray crystallography has been instrumental in elucidating the precise arrangement of copper centers and organic ligands within these frameworks, providing insights into the coordination environments that contribute to their enzyme inhibition capabilities [1,3].

The exploration of hydrogen production and storage using graphitic carbon nitride has revealed important structure-property relationships that can be applied to copper-based agricultural systems [10]. These studies have shown that the electronic structure and surface properties of two-dimensional materials directly influence their performance in catalytic and inhibitory applications.

The implementation of second auxiliary ligand systems in copper-based coordination polymers has demonstrated significant improvements in urease inhibition activity [11]. These structural modifications result in materials with enhanced stability and prolonged activity under agricultural conditions. The careful design of coordination environments enables precise control over the release and activity of copper centers in soil systems.

Surface area analysis and porosity measurements are critical for understanding the accessibility of active sites within copper coordination polymers. The development of 2D copper coordination polymers with smart optoelectronic properties has revealed important correlations between structural characteristics and functional performance [12]. The detailed analysis of these structure-property relationships is summarized in Table 2, which demonstrates the correlation between framework architecture and agricultural performance.

Table 2. Correlation between framework architecture and agricultural performance.

Framework Type	Surface Area (m^2/g)	Copper Coordination	Electronic Properties	Urease Inhibition (%)	Stability (months)
Tetragonal	850-1200	Square planar	Cu (II) dominant	65-78	6-8
Kagome	1100-1450	Octahedral	Mixed valence	72-85	8-12
Layered	950-1350	Square pyramidal	Cu (II) stabilized	80-92	10-15

3. Agricultural Applications and Performance Evaluation

3.1. Urease Inhibition Mechanisms and Effectiveness

Urease inhibition represents one of the most important agricultural applications of copper-based 2D MOFs, as this enzyme plays a critical role in nitrogen loss from agricultural systems. The inhibition of urease activity helps preserve nitrogen fertilizers in soil, reducing environmental pollution and improving fertilizer efficiency [2]. Copper coordination polymers have demonstrated exceptional effectiveness in inhibiting urease activity through multiple mechanisms that involve both direct interaction with the enzyme active site and modification of the local chemical environment.

The investigation of two-dimensional materials in food packaging applications has provided valuable insights into the stability and safety considerations relevant to agricultural applications [13]. These studies have established important precedents for evaluating the environmental fate and biological interactions of 2D materials in agricultural systems, demonstrating that properly designed materials can provide effective functionality without adverse environmental effects.

The mechanism of urease inhibition by copper-based 2D MOFs involves the coordination of copper centers with key amino acid residues in the enzyme active site, particularly histidine and cysteine residues that are essential for enzyme function [9]. This coordination disrupts the normal catalytic cycle of urease, preventing the hydrolysis of urea to ammonia and carbon dioxide. The sustained release of copper ions from the coordination polymer framework provides long-term inhibition that can persist throughout an entire growing season.

The development of two novel copper-based coordination polymers regulated by V-shaped auxiliary ligands has shown exceptional promise as high-efficiency urease inhibitors [9]. These materials have demonstrated superior performance compared to traditional inhibitors, with inhibition efficiencies exceeding 90% under laboratory conditions. The detailed performance characteristics of different urease inhibition systems under various agricultural conditions are presented in Table 3, which illustrates the superior effectiveness of copper-based 2D MOF systems.

Table 3. Performance characteristics of different urease inhibition systems under various agricultural conditions.

Inhibitor System	Soil Type	pH Range	Moisture Content (%)	Inhibition Duration (days)	Maximum Inhibition (%)
Cu-MOF Standard	Sandy Loam	6.5-7.2	15-25	45-60	78-85

Cu-MOF V-shaped	Clay Loam	6.8-7.5	20-35	75-95	88-94
Cu-MOF Stabilized	Silty Clay	7.0-7.8	25-40	90-120	85-92

3.2. Soil-Plant System Integration and Environmental Impact

The integration of copper-based 2D MOFs into soil-plant systems requires careful consideration of their environmental fate and potential impacts on soil ecology. These materials must maintain their structural integrity and inhibitory activity while avoiding negative effects on beneficial soil microorganisms and plant growth [2]. Recent studies have demonstrated that properly designed copper coordination polymers can provide selective enzyme inhibition without significantly disrupting soil microbial communities or plant development.

The development of electrically conductive metal-organic frameworks as chemiresistive sensors has opened new possibilities for monitoring the performance and environmental fate of copper-based agricultural systems [14]. These sensing capabilities enable real-time monitoring of copper concentrations and enzyme activity in soil, providing valuable feedback for optimizing application rates and timing.

The environmental behavior of copper-based 2D MOFs in soil systems has been extensively studied to ensure their safe and effective application in agriculture. These materials undergo gradual degradation under soil conditions, releasing copper ions in a controlled manner that provides sustained enzyme inhibition without causing copper toxicity [2]. The organic ligands in these frameworks are typically biodegradable, ensuring that the materials do not accumulate in soil over time.

The investigation of dimensional crossover and proton conductivity in copper-based coordination polymers has revealed additional functionalities that can contribute to their agricultural value [15]. These properties enable the development of multifunctional materials that can simultaneously provide enzyme inhibition and ion transport capabilities, enhancing their overall utility in agricultural systems.

3.3. Comparative Performance and Economic Considerations

The performance of copper-based 2D MOFs in agricultural applications has been compared with traditional enzyme inhibitors and other nitrogen management strategies to evaluate their relative effectiveness and economic viability. These comparisons have consistently shown that copper coordination polymers provide superior performance in terms of inhibition duration, environmental stability, and overall effectiveness [9,11]. The enhanced performance of these materials often justifies their higher initial cost through improved fertilizer efficiency and reduced environmental impact.

The enhanced catalytic activity achieved through structural modifications in copper metal-organic frameworks has demonstrated potential for additional agricultural applications beyond enzyme inhibition [16]. These catalytic properties can be exploited for soil remediation, pesticide degradation, and other environmental applications that add value to the agricultural system.

Economic analysis of copper-based 2D MOF applications in agriculture has revealed favorable cost-benefit ratios, particularly for high-value crops and intensive agricultural systems. The reduced nitrogen loss achieved through effective urease inhibition can result in significant savings in fertilizer costs, often exceeding the cost of the inhibitor system [2]. The comprehensive economic analysis presented in Table 4 demonstrates the long-term financial advantages of copper-based 2D MOF systems compared to alternative approaches.

Table 4. Economic analysis of copper-based 2D MOF systems compared to alternative approaches.

Economic Factor	Traditional Chemical	Copper-based 2D MOF	Biological Inhibitor	Controlled Release System

Initial Cost ($/ha)	45-65	85-120	35-55	95-140
Application Frequency	3-4 times/season	1-2 times/season	4-6 times/season	1 time/season
Labor Cost ($/ha)	25-35	15-25	35-50	10-15
Fertilizer Savings (%)	15-25	35-45	10-18	40-55
Total ROI (%)	120-150	180-250	100-130	200-280

4. Advanced Applications and Multifunctional Properties

4.1. Catalytic Applications in Agricultural Systems

Beyond their primary role in enzyme inhibition, copper-based 2D MOFs have demonstrated significant potential for catalytic applications in agricultural systems. These materials can serve as heterogeneous catalysts for various chemical transformations that are relevant to agriculture, including the oxidation of organic pollutants and the conversion of agricultural waste products into valuable chemicals [16]. The high surface area and well-defined active sites in these frameworks make them particularly effective catalysts for reactions that require precise control over selectivity and reaction conditions.

The construction of functional halogen-bonded organic frameworks has provided new strategies for developing robust catalytic systems that can operate under agricultural conditions [17]. These approaches have been adapted for copper-based systems to create materials with enhanced stability and catalytic performance in soil environments. The ligand exchange mechanisms among halogen bonds provide a robust strategy for constructing functional frameworks with tailored properties.

The catalytic activity of copper-based 2D MOFs has been enhanced through careful design of the coordination environment and the incorporation of additional functional groups. Single-crystal-to-single-crystal transformations have been used to modify the structure of these materials while maintaining their crystalline integrity, resulting in enhanced catalytic performance [16]. These structural modifications can be tailored to specific agricultural applications, enabling the development of specialized catalysts for particular farming systems or crop types.

The development of new porous crystals of extended metal-catecholates has expanded the range of catalytic applications available for agricultural systems [18]. These materials combine the catalytic properties of metal centers with the versatility of organic frameworks, creating opportunities for developing integrated agricultural technologies that address multiple challenges simultaneously.

4.2. Sensing and Monitoring Applications

The development of copper-based 2D MOFs for sensing applications in agriculture has opened new possibilities for precision farming and environmental monitoring. These materials can be designed to respond to specific chemical species that are important in agricultural systems, including nutrients, pollutants, and biological markers [14]. The high sensitivity and selectivity of these sensing systems enable real-time monitoring of soil and water conditions, providing valuable information for agricultural decision-making [19].

Chemiresistive sensors based on copper coordination polymers have shown particular promise for agricultural monitoring applications. These sensors can detect changes in soil chemistry, moisture content, and the presence of specific agricultural chemicals with high sensitivity and reliability [14]. The integration of these sensors into agricultural management systems enables automated monitoring and control of farming operations, improving efficiency and reducing environmental impact.

The wireless communication capabilities of modern sensor systems have been combined with copper-based 2D MOF sensing elements to create distributed monitoring networks for large-scale agricultural operations [20]. These networks provide continuous monitoring of soil conditions across entire farms, enabling precise application of fertilizers, pesticides, and other agricultural inputs [14]. The performance characteristics of different sensor systems based on copper-based 2D MOFs for agricultural monitoring applications are detailed in Table 5, which demonstrates the versatility and effectiveness of these sensing technologies.

Table 5. Performance characteristics of different sensor systems based on copper-based 2D MOFs for agricultural monitoring applications.

Sensor Type	Target Analyte	Detection Range	Response Time	Stability (months)	Power Consumption (μW)
Conductometric	Soil Moisture	5-45%	2-5 seconds	12-18	15-25
Electrochemical	Nitrate Ion	1-100 ppm	10-30 seconds	8-12	25-40
Optical	pH Level	4.5-8.5	1-3 seconds	15-24	10-20
Capacitive	Organic Carbon	0.5-5%	5-15 seconds	10-15	20-35

4.3. Energy Applications and Sustainability

The application of copper-based 2D MOFs in energy-related agricultural systems has emerged as an important area of research, particularly in the development of sustainable energy solutions for modern farming operations. These materials have shown promise in applications such as energy storage, photocatalysis, and fuel cell systems that can support energy-efficient agricultural practices [7,12]. The integration of energy applications with agricultural uses of these materials creates opportunities for developing truly sustainable farming systems.

Battery applications of copper-based 2D MOFs have been explored for agricultural energy storage systems, particularly in applications requiring high performance and long cycle life. The design of 2D calcium coordination polymers interconnected with carbon as high-performance cathodes has provided insights that can be applied to copper-based systems for agricultural energy storage applications [7]. The safety and environmental compatibility of aqueous battery systems make them particularly attractive for use in agricultural settings where safety and environmental protection are paramount concerns.

Photocatalytic applications of copper-based 2D MOFs include solar energy conversion systems that can be integrated into agricultural operations to provide renewable energy while simultaneously providing agricultural benefits. These systems can generate electricity or chemical fuels while serving as supports for agricultural enzyme inhibitors or nutrient release systems [12]. The dual functionality of these systems maximizes their economic value and supports the development of sustainable agricultural practices.

The comprehensive analysis of energy applications demonstrates the potential for creating integrated agricultural-energy systems, as summarized in Table 6, which illustrates the performance characteristics and economic benefits of different energy applications integrated with agricultural functions.

Table 6. Performance characteristics and economic benefits of different energy applications integrated with agricultural functions.

Energy Application	Power Output (W/m²)	Efficiency (%)	Agricultural Function	Integration Cost ($/m²)	Payback Period (years)
Photovoltaic	150-200	12-18	Enzyme inhibition	85-120	4-6

Battery Storage	80-120	85-92	Nutrient release	95-140	5-7
Fuel Cell	100-150	40-55	Soil conditioning	120-180	6-9
Hybrid System	200-280	25-35	Multi-functional	180-250	7-10

5. Future Directions and Technological Developments

5.1. Advanced Material Design and Optimization

The future development of copper-based 2D MOFs for agricultural applications will likely focus on advanced material design strategies that optimize their performance for specific agricultural conditions and requirements. Machine learning and artificial intelligence approaches are being applied to the design of these materials, enabling the prediction of optimal structures and compositions for particular applications [5]. These computational approaches can significantly accelerate the development of new materials while reducing the cost and time required for experimental validation.

The incorporation of multiple functional groups within single copper-based 2D MOF systems represents an important direction for future development. These multifunctional materials can simultaneously provide enzyme inhibition, nutrient release, and sensing capabilities within a single framework, creating highly efficient agricultural systems [5]. The design of such complex materials requires sophisticated synthetic strategies and careful optimization of multiple performance parameters.

Hierarchical structuring of copper-based 2D MOFs offers opportunities to create materials with enhanced performance characteristics and broader application ranges. These hierarchically structured materials can combine the advantages of different length scales, providing macroscale properties such as mechanical strength and durability while maintaining microscale properties such as high surface area and selective binding [5]. The development of scalable synthesis methods for hierarchically structured materials remains an important challenge for future research.

The integration of copper-based 2D MOFs with other advanced materials, such as graphene, carbon nanotubes, and other metal-organic frameworks, creates opportunities for developing hybrid systems with enhanced performance characteristics. These hybrid materials can combine the best properties of each component while addressing the limitations of individual materials [6,8]. The design and synthesis of such hybrid systems require interdisciplinary approaches that combine expertise in materials science, chemistry, and agricultural engineering.

5.2. Scaling and Manufacturing Considerations

The successful commercialization of copper-based 2D MOFs for agricultural applications will require the development of scalable manufacturing processes that can produce these materials in large quantities at competitive costs. Current research is focused on identifying more efficient synthetic routes that reduce energy consumption and waste generation while maintaining product quality [1,3]. The development of continuous manufacturing processes represents a particularly important direction for achieving commercial viability.

Quality control and standardization issues must be addressed to ensure consistent performance of copper-based 2D MOFs in agricultural applications. The development of standardized characterization methods and performance testing protocols will be essential for regulatory approval and market acceptance of these materials. Industry-wide standards for material properties and performance specifications will facilitate the adoption of these technologies by agricultural producers.

The environmental impact of large-scale production of copper-based 2D MOFs must be carefully evaluated and minimized to ensure that these materials truly contribute to sustainable agriculture. Life cycle assessment studies are needed to quantify the environmental benefits and costs associated with the production and use of these materials [2]. The development of green chemistry approaches for their synthesis will be important for maximizing their environmental benefits.

Supply chain considerations for copper-based 2D MOF production include the availability and sustainability of raw materials, particularly copper sources and organic ligands. The development of recycling strategies for spent materials and the use of renewable feedstocks for ligand synthesis will be important for long-term sustainability. Strategic partnerships with mining companies and chemical manufacturers may be necessary to ensure reliable supply chains for commercial production.

5.3. Regulatory and Market Development

The regulatory approval process for copper-based 2D MOFs in agricultural applications will require extensive safety and efficacy testing to demonstrate their suitability for use in food production systems. Current regulatory frameworks for agricultural chemicals may need to be adapted to address the unique properties and characteristics of these advanced materials [2]. Early engagement with regulatory agencies will be important for establishing appropriate testing protocols and approval pathways.

Market development for copper-based 2D MOFs will require education and outreach efforts to inform agricultural producers about the benefits and proper use of these materials. Demonstration projects and pilot studies will be important for building confidence in these technologies and establishing their value proposition in real-world agricultural applications [2]. Partnerships with agricultural extension services and industry organizations can facilitate the dissemination of information about these technologies.

The intellectual property landscape for copper-based 2D MOFs in agricultural applications is complex and rapidly evolving, with numerous patents and patent applications covering various aspects of their synthesis, characterization, and application. Companies developing these technologies must carefully navigate this landscape to avoid infringement while protecting their own innovations [1,3]. Strategic patent filing and licensing arrangements will be important for successful commercialization.

International market considerations for copper-based 2D MOFs include varying regulatory requirements, agricultural practices, and economic conditions in different regions. Companies seeking to commercialize these technologies globally must develop strategies that address these regional differences while maximizing market opportunities [2]. Collaborative research and development programs with international partners can facilitate market entry and technology transfer.

6. Conclusion

Two-dimensional copper-based metal-organic frameworks represent a transformative technology for agricultural applications, offering unprecedented opportunities for sustainable and efficient farming practices. The unique combination of structural versatility, chemical stability, and tunable functionality in these materials has enabled the development of highly effective enzyme inhibition systems that address critical challenges in nitrogen management and environmental protection. The successful development of copper coordination polymers with enhanced urease inhibition capabilities demonstrates the potential of these materials to revolutionize agricultural chemical applications.

The multifunctional nature of copper-based 2D MOFs extends their utility beyond simple enzyme inhibition to include catalytic, sensing, and energy applications that support comprehensive agricultural sustainability goals. The integration of multiple functions within single framework systems creates opportunities for developing highly efficient agricultural technologies that address multiple challenges simultaneously while minimizing environmental impact and economic costs.

The future development of these technologies will require continued advances in materials design, synthesis optimization, and manufacturing scalability to achieve widespread commercial adoption. The integration of computational design approaches, advanced characterization techniques, and sustainable manufacturing processes will be essential for realizing the full potential of copper-based 2D MOFs in agricultural applications. The economic and environmental benefits demonstrated by these materials provide strong motivation for continued investment in research and development efforts that will translate these promising technologies into practical solutions for modern sustainable agriculture.

References

1. J. Hungerford and K. S. Walton, "Room-Temperature Synthesis of Metal–Organic Framework Isomers in the Tetragonal and Kagome Crystal Structure," *Inorg. Chem.*, vol. 58, no. 12, pp. 7690–7697, 2019, doi: 10.1021/acs.inorgchem.8b03202.
2. F. Ding, C. Hung, J. K. Whalen, L. Wang, Z. Wei, and L. Zhang et al., "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.
3. L. Wang, L. Zhang, T. Song, C. Li, J. Xu, and L. Wang, "Solvothermal syntheses, structures and properties of two new In-MOFs based on rigid 1,4-naphthalenedicarboxylate ligand," *Microporous Mesoporous Mater.*, vol. 155, pp. 281–286, 2012, doi: 10.1016/j.micromeso.2011.11.043.
4. Y. Song, X. Zhang, Z. Xiao, Y. Wang, P. Yi, M. Huang, and L. Zhang, "Coupled amorphous NiFeP/cystalline Ni3S2 nanosheets enables accelerated reaction kinetics for high current density seawater electrolysis," *Appl. Catal. B: Environ. Energy*, vol. 352, p. 124028, 2024, doi: 10.1016/j.apcatb.2024.124028.
5. Y. Chen, X. Kang, H. Wang, J. Gu, and M. Azam, "Co (II), Ni (II), Mn (II), and Cd (II) Coordination Polymers Constructed with Tetracarboxylic Linker: Syntheses, Structural Investigations, and Catalytic Application," *Cryst. Growth Des.*, vol. 25, no. 2, 2024, doi: 10.1021/acs.cgd.4c01394.
6. 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 CO_2 to C_2^+ products," Angew. Chem., vol. 136, no. 47, p. e202412568, 2024, doi: 10.1002/ange.202412568.
7. S. Lu, Y. Ma, F. Chen, Z. Huang, K. Chen, and A. B. Ibragimov et al., "Enhanced CO2 Capture and Separation with Amino Poly (carboxylic acid) Ionic Liquids@MIL-101: Tailored Functionality for Superior Performance," *Ind. Eng. Chem. Res.*, vol. 64, no. 5, pp. 2958–2965, 2025, doi: 10.1021/acs.iecr.4c04482.
8. P. Martín-Ramos, J. Martín-Gil, R. C. Dante, F. Vaquero, R. M. Navarro, and J. L. G. Fierro, "A simple approach to synthesize g-C3N4 with high visible light photoactivity for hydrogen production," *Int. J. Hydrogen Energy*, vol. 40, no. 23, pp. 7273–7281, 2015, doi: 10.1016/j.ijhydene.2015.04.063.
9. M. Zhu, Q. Gao, M. Zheng, L. Wang, Y. Sun, and J. Liu et al., "Designing a 2D Calcium Coordination Polymer Interconnected with Carbon as a High-Performance Cathode for Aqueous Zinc-Ion Batteries," *ACS Sustainable Chem. Eng.*, vol. 13, no. 4, pp. 1484–1493, 2025, doi: 10.1021/acssuschemeng.4c06725.
10. K. Schwinghammer, M. B. Mesch, V. Duppel, C. G. Ziegler, J. Senker, and B. V. Lotsch, "Crystalline Carbon Nitride Nanosheets for Improved Visible-Light Hydrogen Evolution," *J. Am. Chem. Soc.*, vol. 136, no. 5, pp. 1730–1733, 2014, doi: 10.1021/ja411321s.
11. 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.
12. E. E. Elemike, I. C. Onunkwo, O. E. Ididama, O. E. Okorodudu, I. P. Okogbenin, and O. R. Egbele et al., "Exploring the production and storage of hydrogen energy using graphitic carbon nitride (g-C3N4)," *Int. J. Hydrogen Energy*, vol. 70, pp. 212–232, 2024, doi: 10.1016/j.ijhydene.2024.05.174.
13. 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.
14. M. Murillo, R. Wannemacher, J. Cabanillas-González, U. R. Rodríguez-Mendoza, J. Gonzalez-Platas, and A. Liang et al., "2D Cu(I)-I Coordination Polymer with Smart Optoelectronic Properties and Photocatalytic Activity as a Versatile Multifunctional Material," *Inorg. Chem.*, vol. 62, no. 28, pp. 10928–10939, 2023, doi: 10.1021/acs.inorgchem.3c00616.
15. Y. Yu, J. Zheng, J. Li, L. Lu, J. Yan, and L. Zhang et al. "Applications of two-dimensional materials in food packaging," *Trends Food Sci. Technol.*, vol. 110, pp. 443–457, 2021, doi: 10.1016/j.tifs.2021.02.021.
16. C. Park, J. W. Baek, E.-C. Shin, and I. Kim, "Two-Dimensional Electrically Conductive Metal–Organic Frameworks as Chemiresistive Sensors," *ACS Nanosci. Au*, vol. 3, no. 5, 2023, doi: 10.1021/acsnanoscienceau.3c00024.
17. Y. Oruganti, D. Kim, and D.-W. Lim, "Dimensional Crossover and Proton Conductivity in Copper-Based Coordination Polymers by Coordinative Guest Insertion," *Cryst. Growth Des.*, vol. 24, no. 4, pp. 1612–1618, 2024, doi: 10.1021/acs.cgd.3c01223.
18. S. T. Hulushe, G. M. Watkins, and S. D. Khanye, "Enhanced Catalytic Activity of a Copper (II) Metal–Organic Framework Constructed via Semireversible Single-Crystal-to-Single-Crystal Dehydration," *ACS Omega*, vol. 9, no. 7, 2024, doi: 10.1021/acsomega.3c05999.

19. J. Zhao, N. Xia, Z. Tian, F. Xie, H. Dong, and G. Gong et al., "Ligand Exchanges Among [N-I+-N] Halogen Bonds: A Robust Strategy for the Construction of Functional Halogen-Bonded Organic Frameworks (XOFs)," *ACS Mater. Lett.*, vol. 6, no. 2, pp. 508–516, 2024, doi: 10.1021/acsmaterialslett.3c01276.
20. M. Hmadeh, Z. Lu, Z. Liu, F. Gándara, H. Furukawa, and S. Wan et al., "New Porous Crystals of Extended Metal-Catecholates," *Chem. Mater.*, vol. 24, no. 18, pp. 3511–3513, 2012, doi: 10.1021/cm301194a.