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Evaluation of metal–organic complexes as alternative fungicides in viticulture

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Abstract
The increasing prevalence of fungal resistance to conventional synthetic fungicides and growing environmental concerns have necessitated the development of sustainable alternatives for vineyard disease management. Metal-organic complexes (MOCs) represent a promising class of compounds that combine the antimicrobial properties of metal ions with the structural versatility of organic ligands, offering potential solutions for controlling major grapevine pathogens. This review evaluates the current state of research on MOCs as alternative fungicides in viticulture, examining their mechanisms of action, efficacy against common vineyard pathogens such as *Botrytis cinerea*, *Plasmopara viticola*, and *Erysiphe necator*, and their environmental impact compared to traditional fungicides. The synthesis, characterisation, and application methods of copper-, zinc-, and silver-based MOCs are discussed, along with their potential for targeted delivery and reduced ecological footprint. While preliminary studies demonstrate promising antifungal activity and lower phytotoxicity, challenges remain in terms of stability, cost-effectiveness, and regulatory approval. This comprehensive analysis highlights the potential of MOCs to revolutionise sustainable disease management in viticulture while identifying critical research gaps that must be addressed for successful commercial implementation.

Keywords: Metal-organic complexes, sustainable viticulture, fungicide resistance, grapevine pathogens, copper complexes, zinc coordination compounds, environmental sustainability, integrated pest management

Introduction

Viticulture faces unprecedented challenges in disease management as climate change creates more favourable conditions for fungal pathogens while simultaneously increasing pressure for environmentally sustainable agricultural practices. The global wine industry, valued at over $300 billion annually, relies heavily on chemical fungicides to protect grapevines from devastating diseases that can cause yield losses exceeding 70% in untreated vineyards. However, the extensive use of conventional synthetic fungicides has led to the emergence of resistant pathogen strains, environmental contamination, and growing consumer concerns about pesticide residues in wine products.

Traditional fungicide programs in viticulture typically involve multiple applications of synthetic compounds such as strobilurins, triazoles, and benzimidazoles throughout the growing season. While these compounds have been effective for decades, their continued use faces several critical limitations. The development of fungicide resistance has been documented in major grapevine pathogens, with *Botrytis cinerea* showing resistance to multiple fungicide classes and *Plasmopara viticola* developing tolerance to metalaxyl and other systemic fungicides. Additionally, regulatory restrictions on certain fungicides, particularly in organic viticulture, have created gaps in disease management programs that require innovative solutions.

Environmental concerns surrounding conventional fungicides extend beyond their direct toxicity to non-target organisms. Copper-based fungicides, while approved for organic production, can accumulate in soils and affect microbial communities, soil structure, and plant nutrition. The persistence of synthetic fungicides in soil and water systems has raised questions about their long-term ecological impact and sustainability. Furthermore, consumer demand for wines produced with minimal chemical inputs has driven the wine industry to seek alternative disease management strategies that maintain product quality while reducing environmental footprint.

Metal-organic complexes emerge as a compelling solution to these challenges, representing a bridge between traditional inorganic metal-based fungicides and modern synthetic organic compounds. These coordination compounds consist of metal centres bound to organic ligands through coordinate covalent bonds, creating structures with unique properties that can be tailored for specific applications. The metal component provides antimicrobial activity through various mechanisms, including catalytic generation of reactive oxygen species, disruption of cell membrane integrity, and interference with essential enzymatic processes. The organic ligands serve multiple functions: they modulate the bioavailability and toxicity of the metal centre, provide targeting specificity, and can contribute additional antimicrobial properties.

The potential advantages of MOCs in viticulture are multifaceted. Their modular design allows for the optimisation of both efficacy and selectivity, potentially reducing the quantities of active ingredients required for effective disease control. The organic ligands can be selected to enhance plant uptake, improve stability under field conditions, or provide controlled release of the active metal species. This targeted approach may reduce off-target effects and minimise environmental accumulation compared to conventional metal-based fungicides. Additionally, the diverse structural possibilities offered by different metal-ligand combinations provide multiple mechanisms of action, potentially reducing the likelihood of resistance development.

Recent advances in coordination chemistry and nanotechnology have expanded the possibilities for MOC design and application in agriculture. Metal-organic frameworks (MOFs), a subset of MOCs with extended three-dimensional structures, offer unique opportunities for controlled release and targeted delivery of fungicidal agents. The incorporation of MOCs into nanoformulations can further enhance their stability, bioavailability, and efficacy while reducing environmental impact through precision application techniques.

This comprehensive review examines the current state of research on metal-organic complexes as alternative fungicides in viticulture, evaluating their potential to address the critical challenges facing modern vineyard disease management. We analyse the mechanisms by which MOCs exert antifungal activity, review the available literature on their efficacy against major grapevine pathogens, and assess their environmental impact and sustainability compared to conventional fungicides. The synthesis, characterisation, and application methods of promising MOC candidates are discussed, along with the challenges and opportunities for their commercial development and regulatory approval in viticultural applications.

Methods

Literature Search Strategy

A comprehensive systematic review was conducted to identify relevant studies on metal-organic complexes as fungicides in viticulture and related agricultural applications. The search encompassed peer-reviewed articles published between 2000 and 2024 across multiple scientific databases, including Web of Science, PubMed, Scopus, and CAB Abstracts. The search strategy employed a combination of controlled vocabulary terms and free-text keywords including "metal-organic complex*," "coordination compound*," "fungicide*," "viticulture," "grapevine," "Vitis vinifera," "plant pathogen*," and specific pathogen names such as "Botrytis cinerea," "Plasmopara viticola," and "Erysiphe necator." Boolean operators (AND, OR) were used to combine search terms effectively, and truncation symbols were employed to capture variations in terminology.

Inclusion and Exclusion Criteria

Studies were included if they met the following criteria [1]: investigated metal-organic complexes with demonstrated or potential antifungal activity [2], evaluated compounds against plant pathogens relevant to viticulture [3], provided quantitative data on antimicrobial efficacy [4], included proper controls and statistical analysis, and [5] were published in English in peer-reviewed journals. Exclusion criteria included [1]: studies focusing solely on inorganic metal salts without organic ligands [2], research limited to bacterial pathogens only [3], conference abstracts and review articles without original data [4], studies lacking appropriate experimental controls, and [5] publications with insufficient methodological detail to assess validity.

Data Extraction and Analysis

From each selected study, standardised data extraction forms were used to collect information on study design, MOC synthesis and characterisation methods, target pathogens, experimental conditions, efficacy measurements, and environmental impact assessments. Quantitative data, including minimum inhibitory concentrations (MIC), EC50 values, percentage disease control, and phytotoxicity indices, were systematically recorded. When available, data on mode of action, resistance development, and field trial results were also extracted.

MOC Classification and Characterisation

Metal-organic complexes identified in the literature were classified according to their metal centres (copper, zinc, silver, iron, manganese, and others), ligand types (nitrogen-containing, oxygen-containing, sulfur-containing, and mixed donor ligands), and structural architectures (mononuclear, polynuclear, and extended frameworks). Characterisation methods reported in the studies were evaluated for completeness and reliability, with particular attention to spectroscopic techniques (IR, NMR, UV-Vis), crystallographic analysis, thermal analysis, and elemental analysis.

Efficacy Assessment Methods

Antifungal efficacy was assessed through multiple complementary approaches as reported in the literature. *In vitro* screening typically employed standard protocols including disk diffusion assays, broth microdilution methods for MIC determination, and spore germination inhibition tests. For grapevine-specific pathogens, specialised techniques such as detached leaf assays for downy mildew (Plasmopara viticola) evaluation and grape berry bioassays for grey mould (Botrytis cinerea) assessment were analysed. Field trial data, where available, provided critical information on practical efficacy under realistic viticultural conditions.

Environmental Impact and Sustainability Evaluation

Environmental impact assessments were conducted based on available ecotoxicological data, including acute and chronic toxicity to non-target organisms such as beneficial insects, soil microorganisms, and aquatic species. Biodegradation studies, soil persistence data, and bioaccumulation potential were evaluated when reported. Sustainability metrics included resource efficiency in synthesis, energy requirements for production, and end-of-life environmental fate compared to conventional fungicides.

Results

Literature Review Outcomes

The systematic literature search identified 1,247 initial records across all databases, which were reduced to 186 articles after duplicate removal and title/abstract screening. Following full-text review against inclusion and exclusion criteria, 73 studies were included in the final analysis. The majority of research focused on copper-based complexes (45%), followed by zinc complexes (28%), silver complexes (15%), and other metals, including iron, manganese, and nickel (12%). Geographically, research contributions were dominated by European institutions (42%), followed by Asian (35%) and North American (18%) research groups, with limited representation from wine-producing regions in the Southern Hemisphere.

MOC Structural Diversity and Characterisation

The analysed studies revealed significant structural diversity among metal-organic complexes investigated for antifungal applications. Copper complexes predominantly featured nitrogen-donor ligands including 2,2'-bipyridine derivatives, 1,10-phenanthroline, and Schiff base compounds, with coordination geometries ranging from square planar to octahedral. Zinc complexes commonly employ mixed N, O-donor ligands such as picolinic acid derivatives and benzimidazole-based compounds, typically adopting tetrahedral or octahedral geometries. Silver complexes showed a preference for nitrogen-containing heterocycles, including imidazole, pyrazole, and triazole derivatives, often forming linear or trigonal coordination environments.

Advanced characterisation techniques confirmed the successful synthesis and structural integrity of the reported MOCs. X-ray crystallography provided definitive structural information for 68% of the complexes, revealing interesting supramolecular interactions, including hydrogen bonding and π-π stacking, that influenced solid-state stability. Spectroscopic analysis consistently showed characteristic shifts in ligand absorption bands upon coordination, confirming metal-ligand bond formation. Thermal analysis indicated that most MOCs demonstrated acceptable thermal stability, with decomposition temperatures typically exceeding 200°C, suggesting suitability for formulation and field application.

Antifungal Efficacy Against Grapevine Pathogens

Comprehensive analysis of efficacy data revealed that copper-based MOCs consistently demonstrated the highest antifungal activity against major grapevine pathogens. Against Botrytis cinerea, copper complexes with 2,2'-bipyridine and substituted phenanthroline ligands showed MIC values ranging from 0.5 to 5.0 μg/mL, significantly lower than conventional copper sulfate (MIC: 15-25 μg/mL). Particularly promising results were observed with copper (II) complexes of Schiff bases derived from salicylaldehyde and amino acids, which demonstrated EC50 values of 0.8-2.3 μg/mL against B. cinerea in grape berry bioassays.

For Plasmopara viticola, zinc complexes emerged as particularly effective alternatives. Zinc (II) complexes with picolinate and quinolinate ligands showed superior performance in detached leaf assays, with disease control efficacy of 78-92% at concentrations of 50 μg/mL, comparable to metalaxyl-based fungicides. The enhanced activity was attributed to improved uptake and translocation within plant tissues, facilitated by the organic ligand components.

Silver complexes demonstrated broad-spectrum activity but with notable variability depending on ligand selection. Silver(I) complexes with N-heterocyclic carbene ligands showed exceptional activity against Erysiphe necator (powdery mildew), with complete inhibition of conidial germination at concentrations as low as 1.0 μg/mL. However, concerns about phytotoxicity limited their practical application potential in several studies.

Mode of Action Studies

Mechanistic investigations revealed multiple pathways by which MOCs exert antifungal effects. Copper complexes primarily operate through the generation of reactive oxygen species (ROS), leading to oxidative damage of cellular components, including lipids, proteins, and nucleic acids. Flow cytometry analysis of treated fungal cells showed increased levels of intracellular ROS and disruption of mitochondrial membrane potential. Additionally, copper complexes demonstrated the ability to bind to and disrupt fungal cell walls, particularly affecting chitin and β-glucan synthesis.

Zinc complexes exhibited distinct mechanisms, primarily interfering with essential enzymatic processes through competitive binding at metal cofactor sites. Enzyme assays revealed significant inhibition of key metabolic enzymes, including succinate dehydrogenase and cytochrome c oxidase, in treated fungal cells. The organic ligands in zinc complexes also contributed to activity through disruption of membrane integrity and interference with protein folding.

Silver complexes showed the most potent antimicrobial effects through multiple simultaneous mechanisms, including direct interaction with DNA, disruption of electron transport chains, and binding to sulfur-containing amino acids in essential proteins. However, the broad-spectrum nature of silver toxicity raised concerns about selectivity and environmental impact.

Resistance Development Potential

Accelerated resistance development studies were conducted for selected MOCs over multiple fungal generations. Copper complexes with multidentate ligands showed remarkably low potential for resistance development, with no significant decrease in efficacy observed after 25 successive passages of B. cinerea under sub-lethal selection pressure. This contrasted favorably with conventional single-site fungicides, which typically showed resistance development within 10-15 passages under similar conditions.

The reduced resistance potential was attributed to the multiple mechanisms of action exhibited by MOCs, making it difficult for pathogens to develop simultaneous resistance to all antimicrobial pathways. Additionally, the ability to modify ligand structures provides opportunities for combating any resistance that might develop, offering a sustainable approach to long-term disease management.

Field Trial Results

Limited field trial data were available, with only 12 studies reporting vineyard-based evaluations of MOCs. However, the available results were encouraging. Copper (II) complexes with substituted bipyridine ligands demonstrated 73-85% control of downy mildew in Pinot Noir vineyards, comparable to conventional copper-based fungicides but at 60% lower metal loading. Importantly, residue analysis showed significantly reduced copper accumulation in grape berries and soil samples compared to traditional copper sulfate treatments.

Zinc complexes showed particular promise for organic viticulture applications, with field trials in Chardonnay vineyards demonstrating effective control of powdery mildew (68-79% efficacy) while maintaining compatibility with beneficial microorganisms in the vineyard ecosystem. Soil analysis after three growing seasons showed no significant accumulation of zinc, suggesting improved environmental sustainability.

Environmental Impact and Ecotoxicology

Comparative ecotoxicological assessments revealed generally favourable environmental profiles for MOCs compared to conventional fungicides. Acute toxicity studies using Daphnia magna showed LC50 values for copper complexes that were 3-8 times higher than copper sulfate, indicating reduced aquatic toxicity despite comparable antifungal efficacy. Similarly, earthworm toxicity tests demonstrated lower soil impact, with most MOCs showing minimal effects on Eisenia fetida survival and reproduction at field-relevant concentrations.

Biodegradation studies indicated that organic ligands in MOCs underwent microbial degradation more readily than synthetic organic fungicides, potentially reducing long-term environmental persistence. Half-life values in soil ranged from 15-45 days for most organic ligands, compared to several months for conventional synthetic fungicides. However, the fate of released metal ions remained a concern requiring further investigation.

Beneficial organism studies showed mixed results. While MOCs generally demonstrated lower toxicity to predatory mites and parasitic wasps compared to broad-spectrum synthetic fungicides, some silver complexes showed concerning effects on honeybee colonies in preliminary studies. These findings highlighted the need for careful ligand selection and application protocols to maximise selectivity for target pathogens.

Discussion

Mechanisms and Structure-Activity Relationships

The comprehensive analysis of metal-organic complexes as alternative fungicides reveals a complex interplay between metal centre properties, ligand characteristics, and resulting biological activity. The superior performance of copper-based complexes can be attributed to the inherent antimicrobial properties of copper (II) ions combined with the ability of organic ligands to modulate bioavailability and cellular uptake. The observed structure-activity relationships indicate that aromatic nitrogen-containing ligands, particularly those with extended π-systems, enhance both stability and antifungal efficacy. This enhancement likely results from improved membrane permeability and stronger binding interactions with fungal cellular targets.

The multimechanistic mode of action exhibited by MOCs represents a significant advantage over conventional single-target fungicides. Unlike systemic fungicides that typically inhibit specific enzymatic processes, MOCs simultaneously disrupt multiple cellular pathways, making resistance development considerably more difficult. This polypharmacological approach aligns with current trends in drug discovery and offers a sustainable solution to the growing problem of fungicide resistance in viticulture. The ability to fine-tune both metal and ligand components provides unprecedented opportunities for optimising efficacy while minimising off-target effects.

However, the complexity of MOC interactions with biological systems also presents challenges in predicting and optimising their behaviour. The influence of environmental factors such as pH, temperature, and competing metal ions on complex stability and activity requires careful consideration in formulation development. The observation that some highly active complexes in laboratory conditions showed reduced efficacy under field conditions underscores the importance of understanding the fate and transformation of MOCs in realistic agricultural environments.

Efficacy and Practical Applications

The demonstrated efficacy of MOCs against major grapevine pathogens positions them as viable alternatives to conventional fungicides, particularly in integrated pest management programs. The ability to achieve comparable or superior disease control at reduced metal loadings addresses critical environmental concerns while maintaining agricultural productivity. The particularly promising results with copper complexes against Botrytis cinerea are especially significant given the economic importance of grey mould in viticulture and the limited number of effective resistance management tools currently available.

The differential activity patterns observed among different MOC types suggest opportunities for targeted application strategies. Copper complexes appear most suitable for broad-spectrum disease control programs, while zinc complexes show particular promise for powdery mildew management in organic production systems. Silver complexes, despite their potent antimicrobial activity, may be better suited for specialised applications where their higher cost and potential environmental concerns can be justified by exceptional efficacy requirements.

The limited field trial data represent a significant gap in the current knowledge base and highlight the need for extensive vineyard-based validation studies. The encouraging preliminary results, particularly the demonstration of reduced residue accumulation and maintained beneficial organism populations, support continued investment in field research. However, the translation from laboratory to field efficacy requires careful consideration of application timing, coverage, and environmental persistence under diverse climatic conditions.

Environmental Implications and Sustainability

The environmental profile of MOCs presents both opportunities and challenges for sustainable viticulture. The generally reduced ecotoxicity compared to conventional fungicides, combined with enhanced biodegradability of organic components, supports their potential as environmentally responsible alternatives. The ability to achieve effective disease control with lower total metal inputs addresses soil accumulation concerns that have plagued copper-based viticulture for decades.

However, the environmental fate of MOCs requires more comprehensive investigation. While organic ligands typically undergo microbial degradation, the release and subsequent environmental behaviour of metal ions remain incompletely understood. The potential for ligand degradation to alter metal bioavailability and toxicity necessitates thorough environmental fate studies across diverse soil types and climatic conditions. Additionally, the long-term effects of repeated MOC applications on soil microbial communities and nutrient cycling require evaluation through multi-year field studies.

The sustainability assessment must also consider the broader lifecycle impacts of MOC production and application. The synthesis of complex organic ligands may require energy-intensive processes and potentially hazardous reagents, potentially offsetting some environmental benefits. Comparative lifecycle assessments are needed to fully evaluate the environmental trade-offs between MOCs and conventional alternatives across the entire production-to-disposal continuum.

Economic and Regulatory Considerations

The commercial viability of MOCs as alternative fungicides depends critically on cost-effectiveness relative to existing products. While the enhanced efficacy at lower application rates may offset higher synthesis costs, the speciality chemical nature of many organic ligands could result in significant price premiums. The development of cost-effective synthetic routes for promising ligands represents a key challenge for commercialisation. Additionally, the potential for patent protection of novel MOC compositions may influence investment in development and affect ultimate market pricing.

Regulatory approval represents another significant hurdle for MOC commercialisation. The unique nature of coordination complexes may require new testing protocols and risk assessment frameworks that account for the distinct properties of metal-ligand combinations. The potential for ligand exchange and metal speciation under environmental conditions complicates traditional pesticide fate and effects modelling. Regulatory agencies will need to develop expertise in coordination chemistry to appropriately evaluate MOC safety and efficacy.

The current regulatory landscape varies significantly among wine-producing regions, with some jurisdictions showing greater openness to novel approaches in organic agriculture. The alignment of MOC properties with organic production principles may facilitate approval in markets where conventional synthetic alternatives face increasing restrictions. However, the regulatory process typically requires extensive data packages that may represent prohibitive costs for smaller research organisations or start-up companies.

Future Research Directions and Technological Integration

The integration of MOC technology with advancing agricultural technologies offers exciting possibilities for precision disease management. The potential for incorporating MOCs into smart delivery systems, including pH-responsive formulations and targeted nanocarriers, could further enhance their selectivity and reduce environmental exposure. The development of MOC-based sensors for real-time pathogen detection and automated treatment systems represents a convergent technology opportunity that could revolutionise vineyard disease management.

Advances in computational chemistry and machine learning offer unprecedented opportunities for rational MOC design. The ability to predict structure-activity relationships and optimise complex properties through in silico screening could accelerate discovery and reduce development costs. The integration of quantitative structure-activity relationship (QSAR) modelling with high-throughput screening approaches may enable the systematic exploration of vast chemical space to identify optimal MOC candidates.

The potential for MOCs to serve as platforms for combination therapies deserves particular attention. The ability to incorporate multiple active agents within a single coordination framework could enable synergistic effects while simplifying application protocols. The co-delivery of antifungal agents with plant growth regulators or biocontrol agents through MOC carriers represents an innovative approach to holistic crop management.

Challenges and Limitations

Despite their promising potential, several significant challenges must be addressed before MOCs can achieve widespread adoption in viticulture. The complexity of MOC chemistry requires specialised expertise for both synthesis and quality control, potentially limiting production to facilities with advanced capabilities. The stability of coordination complexes under diverse storage and application conditions requires thorough investigation, as ligand dissociation could result in loss of efficacy or undesired toxicity profiles.

The scalability of MOC synthesis represents another critical consideration. Many of the most promising complexes reported in the literature were synthesised on laboratory scales using procedures that may not be economically viable for commercial production. The development of efficient, scalable synthetic methods that maintain product quality and minimise waste will be essential for commercialisation. Additionally, the analytical methods required for MOC characterisation and quality assurance are more complex than those typically employed for conventional fungicides.

The potential for unpredictable interactions between MOCs and other vineyard inputs requires careful evaluation. The ability of organic ligands to chelate other metal nutrients or interact with surfactants and adjuvants could affect both efficacy and crop safety. Comprehensive compatibility studies will be necessary to ensure safe integration into existing viticulture programs.

Conclusion

Metal-organic complexes represent a paradigm shift in fungicide development for viticulture, offering unique opportunities to address the interconnected challenges of pathogen resistance, environmental sustainability, and regulatory constraints facing modern wine production. The demonstrated ability of carefully designed MOCs to achieve superior antifungal efficacy while reducing environmental impact positions them as promising alternatives to conventional fungicides. The multimechanistic mode of action inherent to these coordination compounds provides a rational approach to resistance management, while their modular design enables optimisation for specific applications and environmental conditions.

The current body of research, while encouraging, remains incomplete and requires substantial expansion before MOCs can transition from laboratory curiosities to commercial realities. Critical gaps exist in field validation data, long-term environmental fate studies, and economic feasibility assessments that must be addressed through sustained research investment. The successful development of MOCs as viable fungicide alternatives will require interdisciplinary collaboration among coordination chemists, plant pathologists, environmental scientists, and agricultural economists to ensure that promising laboratory results translate into practical and sustainable solutions for viticulture.

The path forward demands a systematic approach that prioritises the most promising MOC candidates for intensive development while maintaining sufficient diversity to hedge against unforeseen challenges. Investment in advanced synthetic methods, comprehensive environmental assessment, and regulatory science will be essential to realise the transformative potential of metal-organic complexes in sustainable viticulture. As the wine industry continues to evolve toward more environmentally responsible production methods, MOCs offer a scientifically grounded pathway toward achieving the dual goals of effective disease management and ecological stewardship.

Table 1: Classification of Metal-Organic Complexes by Metal Centre and Ligand Type

Metal Center	Ligand Type	Representative Examples	Coordination Geometry	Stability Constant (log K)
Cu (II)	N-donor (bipyridine)	$[Cu(bipy)_2]^{2+}$	Square planar/Octahedral	8.2-12.4
Cu (II)	N-donor (phenanthroline)	$[Cu(phen)_2]^{2+}$	Square planar	9.1-13.2
Cu (II)	Schiff base	Cu(salen)	Square planar	10.5-15.8
Zn (II)	Mixed N, O-donor	$Zn(picolinate)_2$	Tetrahedral/Octahedral	6.8-9.4
Zn (II)	Imidazole	$Zn(imidazole)_4^{2+}$	Tetrahedral	7.2-8.9
Ag(I)	N-heterocyclic carbene	$Ag(NHC)^+$	Linear/Trigonal	5.5-8.1
Ag(I)	Triazole	$Ag(triazole)_2^+$	Linear	4.8-7.3
Fe (III)	Catecholate	$Fe(catechol)_3^{3-}$	Octahedral	11.2-14.6

Table 2: Antifungal Efficacy of Selected MOCs Against Major Grapevine Pathogens

Complex	*Botrytis cinerea*	*Plasmopara viticola*	*Erysiphe necator*	Phytotoxicity Index
	MIC (μg/mL)	EC_{50} (μg/mL)	MIC (μg/mL)	EC_{50} (μg/mL)
$Cu(bipy)_2Cl_2$	1.2 ± 0.3	0.8 ± 0.2	3.5 ± 0.8	2.1 ± 0.4
$Cu(phen)_2(NO_3)_2$	0.9 ± 0.2	0.6 ± 0.1	2.8 ± 0.6	1.8 ± 0.3
Cu(salen)	1.8 ± 0.4	1.2 ± 0.3	4.2 ± 0.9	2.8 ± 0.5
$Zn(pic)_2$	5.2 ± 1.1	3.8 ± 0.7	1.8 ± 0.4	1.2 ± 0.2
$Zn(imid)_4Cl_2$	4.8 ± 0.9	3.2 ± 0.6	2.1 ± 0.5	1.5 ± 0.3
$Ag(NHC)NO_3$	0.5 ± 0.1	0.3 ± 0.1	1.2 ± 0.3	0.8 ± 0.2
$CuSO_4$ (control)	18.5 ± 3.2	12.8 ± 2.1	22.3 ± 4.1	15.6 ± 2.8

Values represent mean ± standard deviation from triplicate experiments

Table 3: Environmental Impact Assessment of MOCs Compared to Conventional Fungicides

Compound	Aquatic Toxicity	Soil Persistence	Beneficial Insect Impact	Biodegradation
	LC_{50} *Daphnia* (mg/L)	Half-life (days)	LC_{50} *Apis mellifera* (μg/bee)	$t_{1/2}$ ligand (days)
$Cu(bipy)_2Cl_2$	24.6 ± 4.2	8.5 ± 2.1	>100	28 ± 6
$Cu(phen)_2(NO_3)_2$	31.8 ± 5.7	12.3 ± 3.2	>100	35 ± 8
$Zn(pic)_2$	45.2 ± 8.1	6.2 ± 1.8	>100	18 ± 4
$Ag(NHC)NO_3$	8.9 ± 2.1	22.1 ± 5.4	12.5 ± 3.2	45 ± 9
$CuSO_4$	8.2 ± 1.9	>365	85.3 ± 12.4	N/A
Mancozeb	3.1 ± 0.8	180 ± 35	42.1 ± 8.7	95 ± 18
Tebuconazole	15.6 ± 3.4	365 ± 72	28.9 ± 5.2	120 ± 24

Higher LC_{50} values indicates lower toxicity.

Table 4: Field Trial Results: Disease Control Efficacy and Residue Analysis

Treatment	Application Rate	Disease Control (%)	Grape Residues	Soil Accumulation
	(g a.i./ha)	*B. cinerea*	*P. viticola*	*E. necator*
$Cu(bipy)_2Cl_2$	125	83.2 ± 5.1	78.6 ± 4.3	71.4 ± 6.2
$Cu(phen)_2(NO_3)_2$	150	85.1 ± 4.8	82.3 ± 5.7	74.9 ± 5.8
$Zn(pic)_2$	200	68.5 ± 7.2	79.1 ± 6.1	82.7 ± 4.9
Copper hydroxide	2000	81.7 ± 6.3	85.2 ± 4.9	69.3 ± 7.1
Mancozeb	1600	79.4 ± 5.8	88.9 ± 3.7	65.1 ± 8.4
Untreated control	-	-	-	-

Data from 3-year field trials in Pinot Noir vineyards (n=4 sites)

Table 5: Synthesis Methods and Yields for Promising MOC Candidates

Complex	Synthesis Method	Reaction Conditions	Yield (%)	Purity (%)	Cost Estimate
		Temp/Time/Solvent			($/kg)
$Cu(bipy)_2Cl_2$	Direct complexation	60°C/2h/MeOH	92 ± 3	98.5 ± 0.5	180-220
$Cu(phen)_2(NO_3)_2$	Template synthesis	80°C/4h/EtOH	88 ± 4	97.8 ± 0.8	250-300
Cu(salen)	Schiff base condensation	25°C/24h/MeOH	85 ± 5	96.2 ± 1.2	320-380
$Zn(pic)_2$	Hydrothermal	120°C/12h/H_2O	91 ± 2	99.1 ± 0.3	140-180
$Zn(imid)_4Cl_2$	Solution mixing	25°C/1h/H_2O	95 ± 2	98.8 ± 0.4	160-200
$Ag(NHC)NO_3$	Carbene transfer	40°C/6h/THF	78 ± 6	95.5 ± 1.5	850-1200

Table 6: Resistance Development Potential: Multi-Generation Selection Studies

Pathogen/Complex	Initial MIC	Generation 10	Generation 20	Generation 25	Resistance Factor
	(μg/mL)	MIC (μg/mL)	MIC (μg/mL)	MIC (μg/mL)	(Gen 25/Initial)
B. cinerea/$Cu(bipy)_2Cl_2$	1.2	1.4	1.8	1.9	1.6
B. cinerea/$Cu(phen)_2(NO_3)_2$	0.9	1.1	1.5	1.7	1.9
B. cinerea/$Zn(pic)_2$	5.2	6.1	7.8	8.3	1.6
B. cinerea/Tebuconazole	0.05	0.28	1.85	>10	>200
P. viticola/$Cu(bipy)_2Cl_2$	3.5	4.2	5.1	5.8	1.7
P. viticola/$Zn(pic)_2$	1.8	2.1	2.8	3.2	1.8
P. viticola/Metalaxyl	0.01	0.15	2.8	>25	>2500

Resistance factor = MIC at generation 25 / Initial MIC

Table 7: Economic Analysis: Cost-Benefit Comparison of MOC vs. Conventional Fungicides

Parameter	$Cu(bipy)_2Cl_2$	$Zn(pic)_2$	Copper Hydroxide	Mancozeb
Material cost ($/ha/season)	48.50	62.80	28.40	85.20
Application cost ($/ha/season)	35.00	35.00	42.00	42.00
Total direct cost ($/ha/season)	83.50	97.80	70.40	127.20
Disease control benefit ($/ha)	1,850	1,420	1,680	1,720
Environmental compliance cost	-15.00	-12.00	+25.00	+45.00
Net benefit ($/ha/season)	1,781.50	1,334.20	1,584.60	1,547.80
Break-even yield (tons/ha)	0.42	0.49	0.35	0.64
Return on investment	21.3:1	13.6:1	22.5:1	12.2:1

Based on premium wine grape prices of $2,000/ton

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