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MINI REVIEW

Eco-Friendly Polyphenol-Mediated Copper Nanoparticles as Promising Antibacterial Agents against *Ralstonia solanacearum*

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ABSTRACT

Ralstonia solanacearum is a soil-borne phytopathogen responsible for bacterial wilt in a wide range of economically important crops worldwide. Its broad host range, environmental persistence, genetic heterogeneity, and strong biofilm-forming capacity significantly restrict the effectiveness of conventional disease management strategies. Despite the use of resistant cultivars and chemical bactericides, sustainable control under field conditions remains inconsistent. Nanotechnology-based antimicrobial systems have recently emerged as promising alternatives in plant disease management. This review synthesizes current understanding of the pathogenic mechanisms of *R. solanacearum* and evaluates the antibacterial and antibiofilm potential of eco-friendly, polyphenol-mediated copper nanoparticles (CuNPs). Available evidence indicates that green-synthesized CuNPs exert antibacterial effects through membrane destabilization, reactive oxygen species generation, enzymatic inactivation, suppression of extracellular polysaccharide synthesis, disruption of biofilm architecture, and interference with quorum-sensing-regulated virulence pathways. The integration of plant-derived polyphenols with copper nanomaterials represents a multifunctional and potentially sustainable strategy for bacterial wilt management.

Keywords: *Ralstonia solanacearum*; Bacterial wilt; Copper nanoparticles; Polyphenols; Biofilm inhibition; Green nanotechnology

INTRODUCTION

Bacterial wilt caused by *Ralstonia solanacearum* is widely recognized as one of the most destructive plant bacterial diseases^{1, 2}. The pathogen infects more than 300 plant species, including several solanaceous crops of high economic value, and persists across diverse climatic regions². Its epidemiological success is associated with remarkable adaptability, long-term survival in soil and water reservoirs, and efficient colonization of host vascular tissues.

After root entry, *R. solanacearum* multiplies within xylem vessels and produces abundant extracellular polysaccharides (EPS), which obstruct water transport and lead to characteristic wilting symptoms³. Biofilm formation within vascular tissues enhances bacterial aggregation, protects against environmental stress, and increases tolerance to antimicrobial interventions^{4, 5}. These processes are regulated through complex signalling networks, including quorum-sensing systems that coordinate motility, EPS production, and virulence gene expression.



The resilience of *R. solanacearum* highlights the need for innovative and sustainable disease management strategies capable of targeting both planktonic and biofilm-associated bacterial populations.

LIMITATIONS OF CONVENTIONAL MANAGEMENT STRATEGIES

Conventional approaches to bacterial wilt control include chemical bactericides, resistant cultivars, crop rotation, soil amendments, and biological control agents⁶. Although these strategies may reduce disease incidence under certain conditions, their effectiveness is often inconsistent in field settings.

A major limitation arises from the high genetic diversity within the *R. solanacearum* species complex². This variability enables rapid adaptation and contributes to frequent breakdown of host resistance. Resistant cultivars may exhibit region-specific effectiveness and lose durability over time. Chemical bactericides can suppress planktonic populations but are generally less effective against bacteria embedded within biofilms⁴. Repeated chemical application also raises concerns regarding environmental contamination, soil microbial imbalance, and regulatory constraints⁶.

Biological control agents offer environmentally attractive alternatives; however, their performance frequently varies under fluctuating environmental conditions. Importantly, most traditional approaches do not directly target quorum sensing or EPS-mediated biofilm formation, which are central to pathogenic persistence and virulence. These limitations justify exploration of mechanistically distinct antimicrobial strategies.

NANOTECHNOLOGY AS A MODERN ANTIBACTERIAL STRATEGY

Nanotechnology provides innovative platforms for antimicrobial development by leveraging physicochemical properties unique to nanoscale materials⁷. Among metallic nanoparticles, copper-based nanomaterials have attracted considerable attention due to their broad-spectrum antimicrobial activity, affordability, and agricultural applicability^{14, 17-19}.

Copper nanoparticles exert antibacterial effects through multiple complementary mechanisms. Direct interaction with bacterial membranes disrupts structural integrity and increases permeability^{17, 18}. Released copper ions penetrate cells and interact with intracellular targets. Copper-mediated redox cycling promotes generation of reactive oxygen species (ROS), including hydroxyl radicals and superoxide anions, leading to oxidative damage of nucleic acids, proteins, and lipids^{17, 19}. In addition, copper ions bind to thiol and amino groups in

essential enzymes, resulting in metabolic disruption and impaired replication¹⁷.

However, conventional chemical synthesis of nanoparticles often involves toxic reducing agents, limiting environmental compatibility¹³. These concerns have driven increasing interest in green synthesis approaches utilizing plant-derived biomolecules.

ROLE OF POLYPHENOLS IN GREEN NANOPARTICLE SYNTHESIS

Polyphenols are plant-derived secondary metabolites characterized by multiple hydroxylated aromatic rings. They possess well-documented antioxidant, antimicrobial, and antibiofilm activities^{9-11, 16}. Their redox-active functional groups enable reduction of metal ions into stable nanoparticles while simultaneously acting as capping and stabilizing agents¹³.

Green synthesis mediated by polyphenols eliminates hazardous chemical reagents and enhances nanoparticle dispersion stability. Surface functionalization with polyphenolic compounds may facilitate improved interaction with bacterial membranes.

Beyond their synthetic role, polyphenols independently modulate bacterial physiology. They alter membrane permeability, inhibit essential enzymes, reduce motility, and interfere with quorum-sensing signaling pathways^{9-12, 20, 21}. Suppression of quorum sensing indirectly reduces EPS production and biofilm maturation, thereby attenuating virulence. When combined with copper nanoparticles, these effects create a synergistic antibacterial system targeting multiple survival pathways simultaneously¹⁵.

EVIDENCE SUPPORTING POLYPHENOL-MEDIATED COPPER NANOPARTICLES

Experimental studies have demonstrated significant antibacterial activity of green-synthesized CuNPs against bacterial wilt pathogens^{7, 8, 15}. In vitro assays report inhibition of bacterial growth and measurable reductions in viable cell counts. Importantly, antibiofilm activity has been observed, including decreased EPS production and disruption of established biofilm structures^{4, 9}.

Physicochemical characterization techniques confirm formation of stable nanoscale particles with reproducible morphology and surface functionalization¹³. Although most studies remain laboratory-based, the collective findings provide mechanistic plausibility supporting further translational research.



MECHANISTIC MODEL OF ANTIBACTERIAL ACTION

The antibacterial activity of polyphenol-mediated CuNPs is likely multifactorial. Initial electrostatic interactions facilitate nanoparticle attachment to bacterial membranes. Membrane perturbation enhances copper ion uptake and increases permeability^{17, 18}. Intracellular redox reactions generate ROS, resulting in oxidative stress and molecular damage^{17, 19}.

Simultaneously, polyphenolic surface groups may interfere with quorum-sensing autoinducer signalling, reducing transcription of virulence-associated genes^[12,20,21]. Inhibition of EPS biosynthesis compromises biofilm integrity^{4, 9}. The convergence of membrane damage, oxidative stress, metabolic interference, and signalling disruption likely accounts for the observed antibacterial efficacy. Such multipronged activity may reduce the probability of rapid resistance development compared with single-target antimicrobials.

ENVIRONMENTAL AND TRANSLATIONAL SIGNIFICANCE

Green synthesis aligns with sustainable agricultural principles by minimizing toxic by-products¹³. Enhanced antimicrobial efficiency at the nanoscale may permit lower overall metal application rates¹⁹. Moreover, the biofilm-disruptive properties of polyphenol-mediated CuNPs have potential relevance beyond plant pathology, including biomedical settings where biofilm-associated infections remain difficult to treat¹⁸.

FUTURE PERSPECTIVES

Before large-scale agricultural implementation, several aspects require further investigation, including standardization of synthesis protocols, comprehensive toxicological evaluation, assessment of soil microbiome impact, plant compatibility testing, and long-term field validation under diverse agro-ecological conditions^{7, 8}. Advanced molecular studies exploring nano-pathogen-host interactions will strengthen mechanistic understanding and inform safe deployment strategies.

CONCLUSION

Eco-friendly polyphenol-mediated copper nanoparticles represent a mechanistically versatile and environmentally conscious antibacterial strategy against *Ralstonia solanacearum*. Their combined effects on membrane integrity, oxidative stress induction, enzymatic inhibition, biofilm suppression, and quorum-sensing interference position them as promising alternatives to conventional bactericides. Continued interdisciplinary research integrating plant pathology, nanotechnology, and

environmental science will determine their practical role in sustainable bacterial wilt management.

DISCLOSURE

Conflict of Interest: The authors declare no conflicts of interest.

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