

Editorial

Innovative frontiers in managing Phytophthora diseases of Citrus: From Conventional protection to Precision plant health

Citrus remains one of the most economically important fruit crops worldwide. However, diseases caused by *Phytophthora* species continue to challenge sustainable citrus production. Foot rot, gummosis, root rot, damping-off and fruit brown rot collectively account for substantial economic losses, particularly in citrus-growing regions of India. Despite decades of research, the soil-borne nature of these pathogens, their prolonged survival through chlamydospores and oospores and their close association with environmental factors make disease management difficult.

In India, the situation is particularly alarming in Nagpur mandarin-growing regions where disease incidence often reaches epidemic proportions during periods of high rainfall and soil moisture. Traditional management strategies based on fungicides and cultural practices have provided significant benefits, yet long-term sustainability requires a paradigm shift toward integrated and technology-driven solutions.

Understanding the pathosystem in the era of omics

The last decade has witnessed unprecedented advances in our understanding of the citrus–*Phytophthora* interaction. Genome sequencing of both host and pathogen has enabled researchers to identify virulence-associated effector proteins and host defense pathways. Comparative transcriptomics has revealed distinct gene expression patterns in resistant and susceptible citrus genotypes, while metabolomic studies have identified defense-related compounds associated with disease resistance.

Multi-omics platforms now permit simultaneous examination of genomic, transcriptomic, proteomic and metabolomic responses during infection. These approaches are helping researchers to identify novel biomarkers for resistance and providing new targets for breeding and disease intervention strategies. Such knowledge is transforming plant pathology from descriptive science into predictive biology.

Biotechnology reshaping disease management

Recent global research demonstrates that biotechnology is becoming a central pillar of citrus disease management. Gene-editing technologies, particularly CRISPR/Cas systems are being explored to modify susceptibility genes and enhance host resistance. Unlike conventional breeding, genome editing offers precision, speed and the possibility of introducing resistance without altering desirable horticultural traits.

RNA interference (RNAi)-based technologies represent another exciting frontier. Host-induced gene silencing and spray-induced gene silencing approaches have shown potential for suppressing essential pathogen genes and reducing disease development. These technologies may eventually provide environmentally safe alternatives to repeated fungicide applications.

Marker-assisted selection, genomic selection and quantitative trait locus mapping are accelerating the development of resistant rootstocks. The identification of genomic regions associated with tolerance to *Phytophthora* infection is facilitating the creation of next-generation citrus planting materials capable of withstanding multiple biotic and abiotic stresses.

The emerging role of the Citrus microbiome

One of the most exciting developments in plant pathology is the growing recognition of the plant microbiome as a critical determinant of plant health. Recent studies suggest that beneficial microorganisms can function as an extended immune system for plants.

Species of *Trichoderma*, *Pseudomonas*, *Bacillus* and other rhizosphere-associated microbes not only suppress *Phytophthora* populations but also stimulate host defense responses. Advanced metagenomic analyses are

enabling researchers to identify microbial communities associated with disease suppression. Future efforts may focus on designing synthetic microbial consortia tailored to specific agroecosystems and disease scenarios.

Precision agriculture and artificial intelligence

The integration of plant pathology with digital agriculture is opening new opportunities for disease forecasting and management. Drones equipped with multispectral and thermal imaging sensors can identify early disease symptoms before visual manifestations become apparent. Satellite imagery and remote sensing technologies provide real-time information on crop health across large production areas.

Artificial intelligence and machine-learning algorithms are increasingly being employed to analyze weather data, soil parameters and disease incidence records. Such systems can generate predictive models that help growers implement timely interventions and optimize resource use. The transition from reactive disease management to predictive disease management represents one of the most significant transformations in modern agriculture.

Nanotechnology and novel delivery systems

Nanotechnology is emerging as another promising tool in citrus disease management. Biogenic nanoparticles synthesized using beneficial microorganisms have shown remarkable antifungal activity against *Phytophthora* species. Nano-formulations may improve the stability, efficacy and targeted delivery of fungicides, biological agents and plant defense stimulants while reducing environmental contamination.

Research on nanoparticle-mediated delivery of RNA molecules and bioactive compounds is progressing rapidly and may eventually provide highly specific disease management solutions.

Toward sustainable integrated disease management

Despite the promise of emerging technologies, no single approach is likely to provide complete and durable control of *Phytophthora* diseases. The future lies in integrating resistant rootstocks, healthy nursery production systems, biological control agents, botanicals, precision irrigation, predictive forecasting models and judicious fungicide use within a comprehensive Integrated Disease Management framework.

Climate change further reinforces the need for such holistic approaches. Increasing weather variability, extreme rainfall events and fluctuating temperatures may alter disease epidemiology and create new challenges for citrus production systems. Adaptive and resilient disease management strategies will therefore become increasingly important.

Future perspectives

The battle against *Phytophthora* diseases is entering a transformative phase. Advances in genomics, genome editing, microbiome science, artificial intelligence, remote sensing and nanotechnology are collectively redefining disease management strategies. The convergence of these disciplines provides unprecedented opportunities to develop environmentally sound, economically viable and scientifically robust solutions.

The future citrus orchard will likely be characterized by disease-resistant rootstocks developed through genomic technologies, microbial communities engineered for enhanced protection, AI-based disease forecasting systems and precision interventions guided by real-time field data. Such innovations offer hope that the long-standing challenge of *Phytophthora* diseases can be addressed more effectively than ever before.

The challenge before plant pathologists is not merely to control disease but to build resilient production systems capable of sustaining citrus cultivation under changing environmental conditions. The integration of biotechnology with ecological principles will undoubtedly shape the next generation of citrus disease management strategies.

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