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[Phuoc V. Nguyen](#)\*, Darnetty Darnetty, Eka Candra Lina, [Nha V. Duong](#), [Phuong T. H. T. B. Ho](#), Di Ba Huynh

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Review

# Nanotechnology for Managing Rice Blast Disease: A Comprehensive Review

Nguyen Van Phuoc <sup>1,2,\*</sup>, Darnetty <sup>1</sup>, Eka Candra Lina <sup>1</sup>, Duong Van Nha <sup>2</sup>, Ho T. H. T. B. Phuong <sup>2</sup> and Huynh Ba Di <sup>2</sup>

<sup>1</sup> Faculty of Agriculture, Andalas University, Padang, West Sumatra, Indonesia

<sup>2</sup> Faculty of Agriculture and Rural Development, Kien Giang University, Kien Giang, Viet Nam

\* Correspondence: nvphuoc@vnkgu.edu.vn

## Abstract

*Magnaporthe oryzae*-induced rice blast remains a critical threat to sustainable rice farming, causing extensive losses in many rice-producing regions worldwide. Due to increasing concerns about pesticide overuse and its impact on the environment and human health, alternative control methods are being actively explored. Nanotechnology has recently gained attention as a potential tool for sustainable disease management. This review summarises current progress in the use of nanomaterials—including metal and biopolymer nanoparticles, nanoemulsions, targeted delivery systems, and biosensors—for the detection and control of rice blast. The mode of action, effectiveness under field conditions, and possible integration into integrated pest management (IPM) programs are discussed. The selection of literature followed the PRISMA-P framework to ensure a systematic and transparent review process. Challenges such as biosafety, environmental risks, and regulatory issues are also addressed, with emphasis on green synthesis methods and the need for field validation before practical application.

**Keywords:** rice blast disease; *Magnaporthe oryzae*; nanoemulsion; antifungal activity; metallic nanoparticles; sustainable disease management

## 1. Introduction

Rice (*Oryza sativa* L.) remains the staple food for over half of the world's population and plays a particularly crucial role in ensuring food security across Asia and Sub-Saharan Africa [1]. However, rice cultivation faces continual threats from biotic stresses, with rice blast disease—caused by the hemibiotrophic fungus *Magnaporthe oryzae* (syn. *Pyricularia oryzae*)—ranking among the most destructive. This pathogen infects all aerial parts of the rice plant, including leaves, stems, nodes, and panicles, often resulting in yield losses exceeding 30% under favorable environmental conditions [2–6]. Although the use of resistant cultivars and fungicides remains central to rice blast management, the rise of new virulent strains and environmental concerns associated with chemical inputs have necessitated alternative strategies [7,8]. In this context, nanotechnology has garnered attention for its potential to deliver targeted, efficient, and environmentally responsible solutions. Nanomaterials such as metallic nanoparticles (Ag, ZnO), nanoemulsions, and biopolymer-based carriers (e.g., chitosan, alginate) have demonstrated antifungal activities and elicitor properties that can enhance host resistance [9–13].

Beyond their therapeutic roles, nano-enabled diagnostic platforms—such as biosensors and nucleic acid nanokits—are being explored for the early detection of *M. oryzae*, enabling timely interventions [14–17]. These approaches align with the principles of integrated pest management (IPM) and may pave the way for more sustainable crop protection systems. Nevertheless, issues concerning nanoparticle persistence, potential phytotoxicity, and environmental impact necessitate further research, particularly regarding green synthesis and regulation [18–22]. This review provides

a critical assessment of recent nanotechnology-based strategies for rice blast control, focusing on mechanisms, efficacy, biosafety, and integration into IPM frameworks.

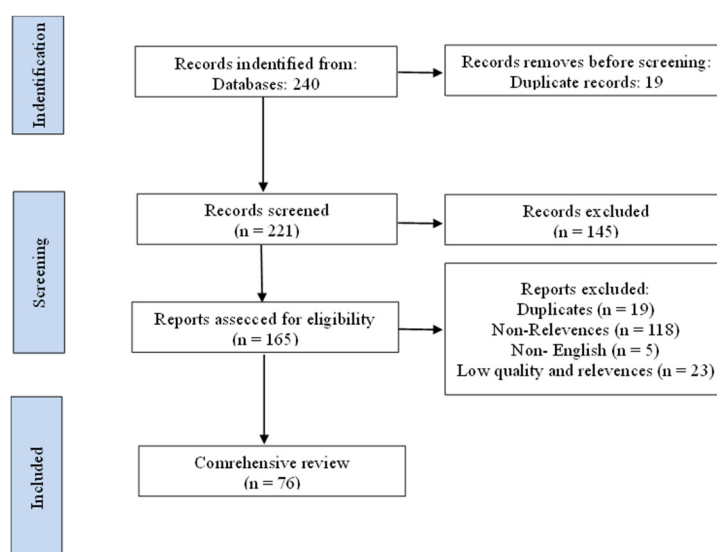
## 2. Methods

The review process adhered to PRISMA-P standards, providing a structured and reproducible approach to literature selection and data synthesis. A comprehensive literature search was carried out to identify relevant peer-reviewed articles published between 2009 and 2025. The search was performed across multiple electronic databases, including PubMed, ScienceDirect, SpringerLink, Elsevier, and Google Scholar.

The search strategy involved a combination of keywords and Boolean operators: “nanotechnology,” “nanoemulsion,” “nanoparticles,” “nano-formulation,” “*Pyricularia oryzae*,” “rice blast disease,” “secondary metabolites,” and “nanotechnology for plant disease management.” Only articles published in English and focusing on the application of nanomaterials in the diagnosis or control of rice blast disease were included.

The selection process consisted of four stages: (i) identification of records through database searching; (ii) screening of titles and abstracts for relevance to the review objectives; (iii) eligibility assessment through full-text reading; and (iv) final inclusion based on scientific quality and relevance to nanotechnology-based rice blast control.

Duplicates, conference abstracts without full texts, non-English publications, and articles unrelated to rice blast or nanotechnology applications were excluded. To enhance the reliability of the selection process, two evaluators reviewed the records separately, and any inconsistencies were reconciled via consensus-based discussion. A flow diagram following the PRISMA format (Figure 1) summarizes the study selection process.



**Figure 1.** The overall research framework of this study outlines.

## 3. Results and Discussions

### 3.1. Metallic Nanoparticles Against *Magnaporthe oryzae*

Metal-based nanoparticles such as silver (AgNPs), copper (CuO, CuChNPs), and zinc oxide (ZnO NPs) have shown consistent antifungal efficacy against *M. oryzae* across laboratory and greenhouse conditions [23–36]. Notably, ZnO NPs inhibit spore germination and suppress appressorium formation while modulating defense gene expression (e.g., *OsNAC4*, *OsPR1b*) and reducing stress-related hormones such as abscisic acid.

These particles exert their antifungal effect by disrupting fungal cell membranes, inducing reactive oxygen species (ROS), and releasing metal ions that compromise cellular function.

Furthermore, they may trigger systemic acquired resistance (SAR), enhancing the plant's innate defense. However, their impact on beneficial rhizosphere microbes remains a concern, underlining the need for targeted delivery and ecological assessment.

### 3.2. Nanoemulsions of Essential Oils

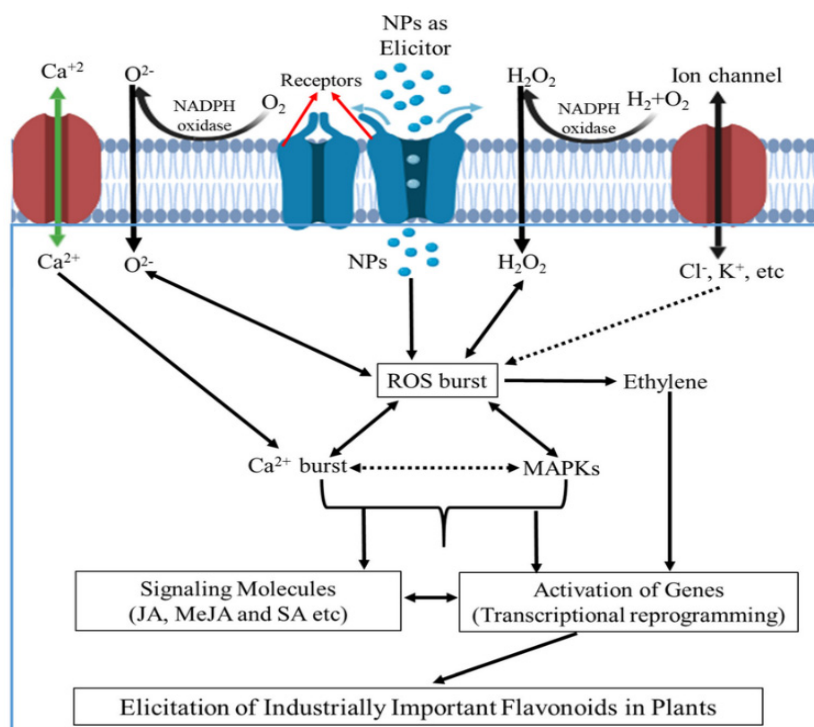
Nanoemulsions prepared with essential oils like neem, citronella, and eugenol have shown promising antifungal properties, largely due to their enhanced dispersion, stability, and ability to penetrate plant tissues efficiently [37–47]. These nano-formulations not only suppress fungal infections but also promote the plant's own defense system by upregulating antioxidant enzymes and activating salicylic acid pathways, all without triggering phytotoxic side effects [48].

The nanoscale droplet size (8–20 nm) ensures intimate contact with fungal structures, while the formulation's resilience under UV and temperature stress enhances field applicability. Scalable methods such as phase inversion temperature (PIT) synthesis have improved their production feasibility. However, field performance varies depending on environmental factors and application timing.

### 3.3. Biopolymer Nanoparticles and Nanochitosan

Natural polymer-based nanoparticles like nanochitosan and nanoalginate are increasingly applied in transporting defense signals and beneficial microbes. These carriers not only possess antifungal effects but also activate plant immune responses, including oxidative bursts and phenolic compound production [12,49–54]. Nanochitosan, in particular, has been shown to suppress key rice pathogens by enhancing antioxidant enzyme activity and biosynthesis of flavonoids and phenols [55–57].

Biopolymeric nanoparticles such as Ag–chitosan, Cu–chitosan, M–CsNPs, and carbon nanospheres (CNs) exhibit strong antifungal activity against *Magnaporthe oryzae* by inhibiting spore germination and disrupting mycelial growth. They also act as elicitors, triggering ROS production, activating antioxidant enzymes, and upregulating plant defense genes. Additionally, their role as carriers for bioactive compounds or antagonistic microbes enables targeted delivery, supporting their integration into sustainable IPM strategies. Recent molecular studies using transcriptomics and metabolomics have begun to elucidate how nano-formulations regulate rice immune pathways and oxidative balance at the cellular level (e.g., upregulation of OsPR1b, OsWRKY45, and PAL genes) Figure 2.



**Figure 2.** Illustrates this nano-elicitation pathway in rice [27].

### 3.4. Smart Nanocarriers for Controlled Release

Stimuli-responsive nanocarriers—such as Pro@MON@PTA, PYR@FeMOF-pectin, and PYR-HMS-HPC—have been developed to enable site-specific fungicide delivery in response to pH, enzyme activity, or redox signals (e.g., glutathione) [58–63].

Such systems enhance foliar adhesion and prolong efficacy under fluctuating environmental conditions. By optimizing release kinetics, these carriers can reduce fungicide doses by up to 50%, offering a balance between efficacy and environmental safety.

### 3.5. Nanosensors for Rapid Diagnosis

Nanosensor-based platforms, including ZnO-imidoester (HINRs) and fluorescein-labeled AgNPs, offer rapid and sensitive detection of *M. oryzae* DNA or pesticide residues such as tricyclazole [14,17,64–66].

The portability and low cost of these biosensors make them ideal for on-site diagnosis. Future developments may include microfluidic-nano hybrids, capable of integrating real-time pathogen monitoring with predictive disease modeling.

### 3.6. Nanomaterials for Enhanced Host Resistance

Silicon-based nanoparticles (SiNPs), carbon nanospheres (CNS), and rice husk ash (RHA)-derived nanosilica have been investigated for their role in enhancing plant resistance [34,67]. These materials can reinforce cell walls, stimulate lignification, and regulate nutrient uptake through gene modulation (e.g., *Lsi1* expression) [36,65,68,69].

CNS, in particular, modulate microbial dynamics in the rhizosphere, contributing to broader disease suppression. SiNPs have also been linked to improved drought and heat tolerance, supporting overall crop resilience.

This comprehensive overview synthesizes the content from Sections 3.1 to 3.6 and serves as a reference for selecting appropriate nano-strategies in integrated pest management, including the comparative properties, mechanisms of action, antifungal effectiveness, advantages, and limitations of various nanomaterials applied in managing rice blast disease (Table 1).

**Table 1.** Comparative overview of nanomaterials for the management of rice blast disease caused by *Magnaporthe oryzae*.

Type of Nanomaterial	Mechanism of Action	Antifungal Effectiveness	Advantages	Challenges / Limitations	References
<b>Metallic NPs (Ag, ZnO, CuO)</b>	Disrupt fungal membranes, generate ROS, release metal ions, trigger SAR	Strong inhibition of spore germination and appressorium formation	High efficacy, dual antimicrobial & defense induction	Toxicity to non-target microbes, accumulation in soil	[23–36]
<b>Nanoemulsions of essential oils</b>	Disrupt fungal structure, enhance antioxidant enzymes (POX, PAL, APX), SA signaling	Moderate to high; enhanced UV and temperature stress	Biodegradable, eco-friendly, stable formulations	Environmental variability affects field performance	[37–48]
<b>Nanochitosan /Biopolymer NPs</b>	Fungistatic effect, act as elicitor, enhance phenolic and ROS response	Moderate; enhanced combined with biocontrol agents	Biocompatible, suitable for seed coating, slow release	Limited penetration, potential formulation instability	[12,49–57]
<b>Smart nanocarriers</b>	Stimuli-responsive release (pH, redox), targeted fungicide delivery	High, with reduced fungicide dose (~50%)	Site-specific delivery, enhanced adhesion, reduced environmental load	High production cost, complex synthesis	[58–63]
<b>Nanosensors / Nano-biosensors</b>	DNA detection, pesticide residue sensing, real-time monitoring	High sensitivity and specificity; early-stage diagnosis	Portable, rapid, low-cost, field applicable	Limited commercial deployment, stability under field conditions	[14,17,64–66]
<b>Silicon-based NPs (SiNPs, CNS, RHA)</b>	Strengthen cell wall, regulate defense genes (Lsi1), lignification	Moderate; also enhance stress tolerance	Enhance host resistance, improve abiotic stress response	Mechanism still under investigation, variable results	[34,36,65,67–69]

Terminology: SAR – systemic immunity response; ROS – oxidative stress molecules; PAL – an enzyme in phenylpropanoid pathway; APX – antioxidant enzyme; SA – key signaling hormone; Lsi1 – silicon transporter gene.

### 3.7. Biosafety and Sustainability Considerations

Environmental and health concerns related to nanoparticle stability, potential toxicity, and their accumulation in ecosystems have driven a shift toward environmentally benign synthesis techniques. Among these, the use of plant-derived compounds or agro-industrial wastes—such as rice straw—has gained attention as sustainable alternatives. Nonetheless, regulatory uncertainties and the lack of harmonized assessment standards remain significant hurdles [18,19,33,70–73].

A case-by-case classification system for nanoformulations, informed by ecotoxicological studies, is essential. Green-synthesized nanomaterials may improve environmental compatibility and public acceptance.

### 3.8. Integration with IPM and Comparative Strategies

Several studies have demonstrated that when nanotechnology is used in tandem with biocontrol species like *Paecilomyces lilacinus*, the outcome in managing plant diseases surpasses that of traditional fungicides including Mancozeb and Carbendazim [6,22,74–76]. This methodology aligns with current trends in IPM, promoting both efficiency and environmental stewardship

When paired with disease forecasting systems and precision delivery, nano-enabled IPM enhances efficacy while minimizing ecological disruption. However, field-scale demonstrations and long-term monitoring are needed to support widespread adoption.

### 3.9. Limitations and Future Perspectives

Although nanotechnology shows great promise in controlling rice blast, several limitations remain. Many nanoformulations effective in the lab show inconsistent results in the field due to environmental variability. Biosafety concerns, including nanoparticle persistence and effects on beneficial microbes, are still unresolved. Moreover, the lack of standardized regulations and high production costs limit large-scale application.

Future research should focus on field validation, eco-toxicological studies, and development of green, cost-effective synthesis methods. Advancing smart delivery systems and integrating nanosensors with precision agriculture tools could significantly improve the effectiveness and sustainability of nano-based disease management. Interdisciplinary collaboration will be essential to address regulatory gaps and support safe deployment in real-world agriculture.

## 4. Conclusion

Nanotechnology offers significant promise for the sustainable management of rice blast disease. Through improved delivery, diagnostic capabilities, and plant defense modulation, nano-based solutions align well with integrated and eco-friendly pest management strategies. Future efforts should prioritize field validation, biosafety assessments, and development of regulatory frameworks that facilitate responsible adoption.

**Conflicts of Interest:** The authors declare no conflict of interest.

**Authors' Declaration:** The authors hereby declare that the work presented in this article is original and that any liability for claims relating to the content of this article will be borne by them.

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