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Review

Significant Roles of Nanomaterials for Enhancing Disease Resistance in Rice: A Review

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Abstract

Rice (*Oryza sativa* L.) is a staple crop for over half of the global population; however, pathogenic infections pose significant threats to its sustainable production. Although chemical pesticides are commonly employed for disease control, their prolonged usage has led to pathogen resistance, reduced effectiveness, and non-target toxicity, rendering them unsustainable for agricultural practices. Nanomaterials (NMs) present a promising alternative due to their small size, tunable release properties, and diverse mechanisms for disease resistance. This review examines how NMs can enhance rice disease management through (1) direct pathogen suppression; (2) the activation of plant defense pathways; (3) the formation of nanoscale barriers on leaves to obstruct pathogens; (4) targeted delivery and controlled release of fungicides; and (5) modulation of the microbiome to bolster resilience. Moreover, we critically analyze the agricultural potential and environmental implications of NMs, develop optimized application strategies, and, for the first time, propose the innovative 'NMs-Rice-Soil' Ternary System framework. This groundbreaking approach integrates nanotechnology, plant physiology, and soil ecology. The pioneering framework offers transformative solutions for sustainable crop protection, illustrating how strategically engineered NMs can synergistically enhance rice productivity, grain quality, and global food security through science-based risk management and interdisciplinary innovation.

Keywords: nanomaterials; rice; disease resistance; systemic resistance; nanorods; nano-pesticides; physical barriers; microbiome

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1. Introduction

Rice (*Oryza sativa* L.) serves as a staple food for over half of the global population and ranks among the most significant cereal crops, with an annual production of approximately 503 million tons [1]. However, pathogenic microorganisms can cause yield losses of up to 30% in rice, resulting in direct economic losses exceeding USD 60 billion annually (IPCC, 2021) and posing persistent threats to global food security [2,3]. Therefore, effective disease control is essential for safeguarding food security. Currently, chemical pesticides are the primary method for managing agricultural diseases due to their high efficiency and rapid action [4]. According to the Food and Agriculture Organization of the United Nations (FAO), global pesticide usage reached 4.2 million tons in 2019, reflecting a 36% increase

since 2000 [5]. The excessive use of conventional pesticides has led to the degradation of agricultural ecosystems and soil health, high pesticide residues, environmental pollution, and the emergence of pesticide resistance [6,7]. Enhancing pesticide transport efficiency in plants is a critical indicator for improving pesticide utilization and a vital strategy for reducing environmental contamination. Consequently, novel and environmentally friendly technological advancements are profoundly significant for achieving high-yield, high-quality, and sustainable global crop production.

Nanotechnology, first proposed by Richard Feynman in 1959, refers to the comprehensive art and technology of manipulating materials at the nanoscale (1–100 nm) to enhance their properties and confer new functionalities [8]. Nanomaterials (NMs) are generally defined as materials with at least one dimension in the 1–100 nm range in three-dimensional space, while nanoparticles (NPs) are materials with all three dimensions within this range [9]. With advancements in nanotechnology, NMs have found extensive applications in physics, chemistry, medicine, electronics, and biology due to their extraordinary characteristics, including surface effects, quantum size effects, volume effects, macroscopic quantum tunneling effects, and interface-related effects [10–14]. Currently, nanotechnology is being implemented in agriculture, facilitating genetically engineered crop projects and promoting sustainable agricultural development [15,16]. Particularly noteworthy is that NMs demonstrate multiple advantages in plant protection, exhibiting synergistic mechanisms such as inhibiting pathogen growth [17], activating systemic resistance in rice [18], and serving as targeted drug delivery carriers [19], thereby significantly improving disease control efficiency. These nanotechnology-based innovative strategies not only effectively ensure crop yields but also reduce dependence on chemical pesticides, providing technical support for improving agricultural product quality and ecological safety while opening new avenues to address global food security challenges.

This review systematically evaluates the application of nanomaterials (NMs) for rice disease management, addressing critical research gaps in the current literature. While existing studies have primarily focused on isolated functions of NMs, our work provides the first comprehensive, pathogen-specific analysis of antimicrobial mechanisms and structure–activity relationships across all major rice pathogens. Beyond fundamental NM–plant interactions, we bridge the gap between laboratory research and practical field applications, incorporating often-overlooked environmental safety assessments to ensure sustainable implementation. Central to this review is the development of a novel 'NMs-Rice-Soil' framework, which unifies materials science and plant pathology to deliver actionable strategies for next-generation rice protection. To achieve this, we pursue four key objectives: (1) elucidating pathogen-specific NM mechanisms, with emphasis on structure-activity relationships; (2) translating nano–bio interactions into scalable, field-compatible solutions; (3) rigorously evaluating environmental trade-offs, including soil microbiome impacts and ecotoxicological risks; and (4) proposing a sustainability roadmap through our framework to balance efficacy with ecological safety. By synthesizing these dimensions, our review advances both theoretical understanding and real-world deployment of nano-agrochemicals, offering a timely contribution to global food security challenges while addressing unresolved questions in agricultural nanotechnology.

2. Literature Search Methodology

The literature search was finalized on 30 April 2025. A standardized four-step analytical approach was employed to systematically screen the academically valuable literature. Firstly, preliminary searches were conducted in the Web of Science database using keywords including "rice", "NPs", "disease", "antibacterial", "nanocomposites", "NMs", and "nanoparticles". The author information, titles, and abstracts of relevant publica-

tions were exported as plain text files. Subsequently, these text files were imported into VOSviewer software (version 1.6.20) for visualization analysis, where 207 keywords with occurrence frequencies exceeding 20 were selected from a total of 16,065 keywords for co-occurrence network analysis, revealing research hotspots and knowledge structures in this field (Figure 1). These studies primarily focus on the toxicity of NMs, their antibacterial activity, and their impact on crop yield and soil. Among these, Ag NPs and Cu NPs are the most widely applied NMs.

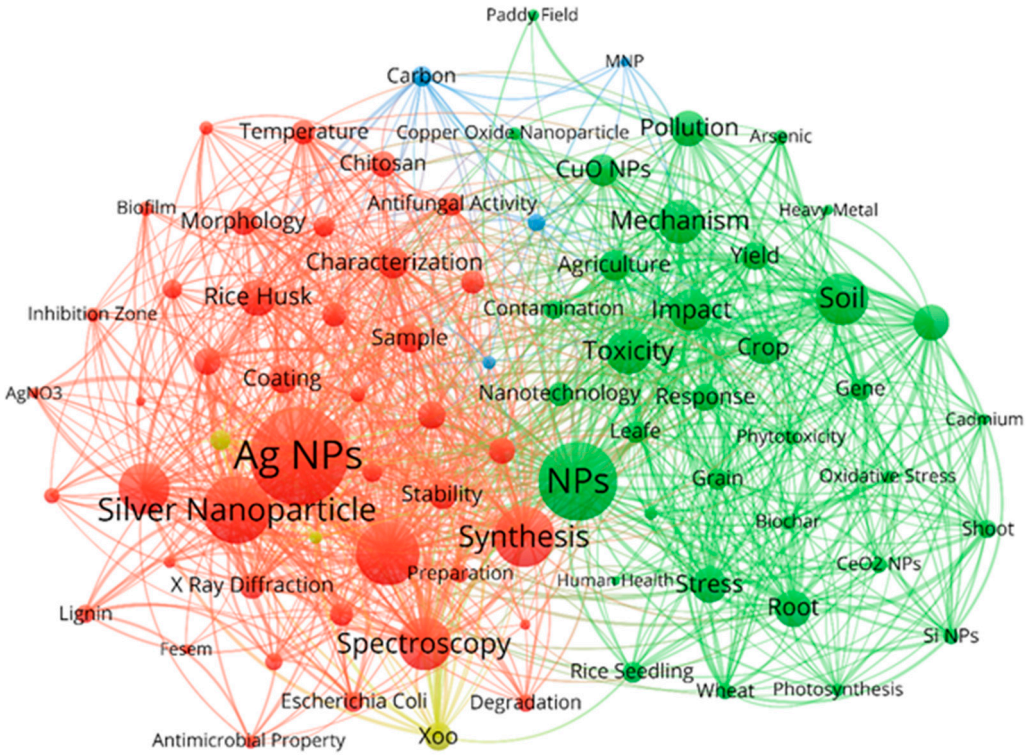
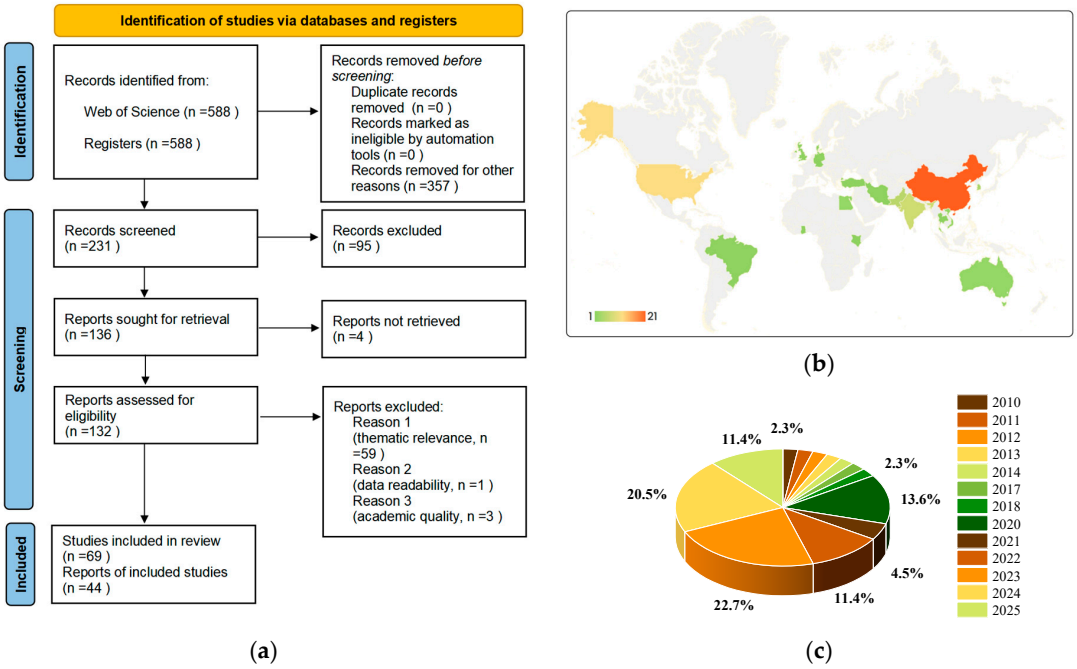


Figure 1. Keyword cluster cloud created by VOS viewer software. The keyword cluster cloud was generated based on the number of publications indexed in Web of Science, where terms with higher occurrence frequencies are displayed in larger font sizes.

Subsequently, building upon the PRISMA framework, we conducted a systematic literature screening based on three core dimensions: thematic relevance, data readability, and academic quality (Figure 2a). We referenced the work of Page et al. [20–22], which outlines the PRISMA 2020 statement—a revised guideline for reporting systematic reviews (BMJ 2021;372:n71. https://doi.org/10.1136/bmj.n71). After the literature screening, we identified a total of 44 publications, indicating a year-on-year increase in the number of papers within this research field (Figure 2c). Following this, we performed a statistical analysis of the countries of publication for these sources. Notably, China and the United States emerged as the leading contributors in terms of publication output regarding NPs for enhancing rice disease resistance (Figure 2b). Finally, selected research papers and review articles that met the inclusion criteria were meticulously examined, and their core content was systematically integrated into this review.



(**a**) (**b**) (**c**)

Figure 2. Literature screening and statistical analysis. (**a**) PRISMA 2020 flow diagram; (**b**) the publication trends of research articles in the field of NMs for enhancing rice disease resistance over the past 15 years. (**c**) Global distribution of research on NMs enhanced rice disease resistance by country. The color gradient represents publication counts by country (data source: Web of Science).

3. NMs-Enhanced Rice Disease Resistance Mechanisms

The key data, including the types of NMs, mechanisms of action, application methods, and research findings, were systematically extracted from each article and compiled into Table 1 for visual presentation. These results collectively demonstrate that NMs have been demonstrated to enhance rice disease resistance primarily through multiple synergistic pathways: directly inhibiting pathogen growth, activating systemic resistance in rice, serving as drug delivery carriers for targeted drug transport, and regulating the microecological balance (Figure 3a).

Table 1. Inhibitory effects and mechanisms of NMs against different pathogens in rice.

Disease	NMs Used [1]	Concentration	Antibacterial Rate (%) [1]	Mechanism	Ref.
F. verticillioides	FeS-NPs	18.00 μg/mL	50.00 (V)	Disrupted membrane integrity.	[23]
	SiO_2 NPs	1.00×10^5 μg/mL	75.00 (F)	Highly induced the expressions of SA-responsive genes.	[24]
		3.00×10^6 μg/mL	85.00 (R)		
	M-CsNPs	2.00×10^5 μg/mL	79.20 (V)	Inhibited spore germination and germ tube elongation by disrupting cell membranes. Enhanced antioxidant enzyme activities and modulated the microbiome.	[25]
		1.00×10^5 μg/mL	70.00 (F)		
M. oryzae	Ag NPs	4.00×10^4 μg/mL	59.00 (S)	Upregulated the expression of immune response-related genes and the relative abundance of signaling-associated metabolites.	[26]
	ZnO NPs	5.00×10^5 μg/mL	61.00 (F)	Reduced conidiation and appressoria formation while inducing defense-related genes, increasing ROS accumulation, and decreasing ABA levels in rice.	[27]
			93.00 (V)		
	GO-PEG-EPXConA	0.18 μg/mL	50.00 (V)	Controlled hyphal growth and inhibited spore germination.	[28]

Table 1. *Cont.*

Disease	NMs Used [1]	Concentration	Antibacterial Rate (%) [1]	Mechanism	Ref.
P. oryzae	Ni-Ch NPs	0.10% (*w*/*v*)	64.00 (V) 23.40 (S)	Disrupted fungal membrane integrity, induced cytoplasmic leakage, and ultimately triggered lytic cell death.	[29]
R. solani	ZnO NPs Ag NPs	450.00 μg/mL	51.10 (V) 61.80 (V)	Penetrated the target pathogen's cell wall and damaged cellular functions.	[30]
	AZOX-AFS-Pec NPs	1.93×10^3 μg/mL 7.50×10^3 μg/mL	50.00 (V) 100.00 (F)	Decreased IAA levels, increased SA levels, and SOD and POD activities in rice plants.	[31]
	$La_{10}Si_6O_{27}$ NRs	1.00×10^5 μg/mL	62.40 (F)	Activated CAM and enhanced antioxidant enzymes, boosted SA production, and strengthened physical barriers.	[18]
	Fe-MOF-PT NPs	2.25×10^3 μg/mL 8.00×10^5 μg/mL	50.00 (V) 59.54 (F)	Induced cellular oxidative stress which damaged cell membranes, mitochondria, and DNA.	[32]
B. oryzae *S. oryzina*	ZnO NPs	50.00 μg/mL	72.78 (V) 85.78 (V)	Reduced spore germination in both strains, disintegrated hyphal, induced cytoplasmic leakage, and collapsed cellular structures.	[33]
Xoo	CS NPs ZnO NPs	8.00 μg/mL	86.76 (V) 73.93 (V)	Suppressed biofilm formation and swimming motility, enhanced SOD activity, induced cell wall and membrane wrinkling and rupture that led to nutrient and nucleic acid leakage.	[34]
	Tm-Ag NPs Al-Ag NPs Sm-Ag NPs	20.00 μg/mL	65.60 (V) 72.10 (V) 68.19 (V)	Direct killed and indirect effected in biofilm formation, swimming, and cell integrity.	[35]
	BNCs	250.00 μg/mL	92.50 (V) 67.10 (F)	Suppressed pathogen growth, motility, and biofilm formation. Induced plant defense responses through upregulated defense genes, enhanced SOD and POD activities, ultimately reshaped rice phyllospheric and root-endophytic microbiota.	[36]
	Ni-SiO_2 NPs	2.00×10^5 μg/mL	89.07 (V) 70.20 (F)	Inhibited biofilm formation, cell injury or death.	[37]
	NiO NPs	200.00 μg/mL	88.68 (V) 69.64 (F)	Reduced the growth and biofilm formation, produced a significant amount of ROS.	[38]
	CuO NPs	50.00 μg/mL	79.65 (V) 67.93 (F)	Wounded the cell membrane, resulting in intracellular content leakage and ROS generation.	[39]
F. Fujikuroi (40) *F. proliferatum* (58) *F. proliferatum* (65)	Ag NPs	12.08 μg/mL	95.56 (V) 70.00 (V) 100.00 (V)	Had not yet been explored.	[40]

[1] Treatment methods of nanomaterials. V: vitro conditions; F: foliar treatment; S: seed soaking; R: root treatment.

NMs show strong direct antibacterial activity against *Xanthomonas oryzae* pv. *oryzae* (Xoo), while systemic resistance induction is more effective against fungal pathogens (*Magnaporthe oryzae*, *Rhizoctonia solani*). The physical barrier mechanism specifically targets *R. solani*, suggesting potential for precision control (Figure 3a). Correlation analysis shows identical sensitivity (r = 1.000) in *Fusarium verticillioides*, *Pyricularia oryzae*, *Bipolaris oryzae*, and *Sphaerulina oryzina*, while *M. oryzae* and *R. solani* share strong fungal targeting (r = 0.956). In contrast, Xoo exhibits unique bacterial responses, underscoring mechanistic divergence between pathogen types. Key findings showed nonsignificant results for pesticide efficiency optimization and microbial regulation, potentially due to sample size or temporal factors (Figure 3b).

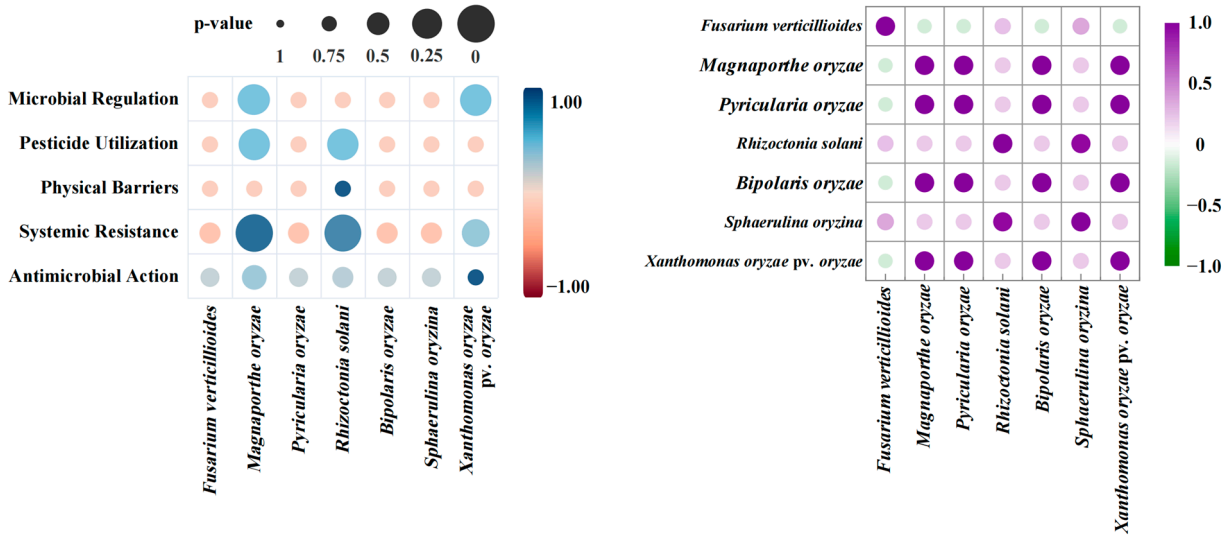


Figure 3. Correlation analysis of rice pathogen responses to NMs' antimicrobial mechanisms. (**a**) Correlation matrix of rice pathogens and NMs antimicrobial mechanisms; (**b**) the inter-pathogen correlation matrix. The color gradient represents Pearson correlation coefficients (ranging from −1 to +1).

However, practical applications necessitate the careful selection of optimal types of NMs based on the characteristics of the target pathogens. From an application perspective, composite NMs with multiple mechanisms may be considered for fungal pathogens, while NMs exhibiting potent direct antimicrobial effects should be prioritized for bacterial diseases. Building upon these findings, the following sections will systematically elaborate on the specific pathways through which NMs enhance rice disease resistance, thereby providing a more comprehensive understanding of their antimicrobial mechanisms. These research outcomes not only deepen our comprehension of NMs-mediated disease resistance but also offer valuable references for precision agriculture practices, establishing a solid theoretical foundation for the development of pathogen-specific nano-pesticides.

3.1. Antimicrobial Action

Certain NMs can adhere to the cell walls of pathogens, alter the structure of lipid bilayers and membrane permeability, penetrate intracellularly, and damage organelles such as mitochondria, ribosomes, and vacuoles. This ultimately inhibits pathogen growth and reproduction [41–43]. Moringa chitosan nanoparticles (M-Cs NPs) induce cellular leakage in pathogens and suppress both the invasion and proliferation of *M. oryzae* within rice leaf cells [26]. In nickel-chitosan nanocomposites (Ni-Ch NPs), electrostatic interactions occur between positively charged nickel ions and negatively charged microbial cell membranes, while chitosan binds to phospholipid components in fungal membranes, leading to cytoplasmic leakage and eventual cell death [44,45]. Culture plates supplemented with 0.1% (*w*/*v*) Ni-Ch NPs exhibited a 64% inhibition rate against *M. oryzae*, effectively enhancing rice blast resistance (Table 1) [45]. Additionally, foliar spraying or seed soaking with ZnO NPs significantly reduced spore germination, mycelial growth, and sporulation of *Helminthosporium oryzae*, thereby mitigating the incidence of rice brown spot disease [46,47].

NMs disrupt biomolecular structures and functions, including DNA, proteins, and lipids, alter intracellular signal transduction, and generate reactive oxygen species (ROS) that induce apoptosis [48,49]. For instance, CuO NPs damage the cell membranes of Xoo, leading to cytoplasmic leakage and ROS production, which inhibit respiration and growth, ultimately reducing the incidence of bacterial leaf blight [40]. ZnO NPs affect pathogen

membrane permeability; their derived ROS (e.g., O_2^-, ·OH, and H_2O_2) enter cells, induce oxidative stress, suppress biofilm formation and motility, and trigger apoptosis, collectively inhibiting the growth of Xoo [50]. M-Cs NPs compromise DNA integrity and stability in *M. oryzae* (Table 1) [26]. Meanwhile, chitosan-iron nanocomposites (BNCs) at a concentration of 250 μg/mL induce ROS accumulation, membrane rupture, and macromolecular (DNA/protein) leakage in Xoo, inhibiting essential biological processes including biofilm formation, swarming motility, and growth rate, exhibiting 92.5% antibacterial activity (Table 1)—significantly higher than that of pure chitosan or FeO NPs [37].

3.2. Induction of Systemic Resistance in Rice

3.2.1. Activation of Rice Immune Responses

NMs can activate both salicylic acid (SA)-mediated Systemic Acquired Resistance (SAR) and jasmonic acid (JA)/ethylene (ET)-mediated Induced Systemic Resistance (ISR), thereby enhancing rice's defense against pathogens. $La_{10}Si_6O_{27}$ nanorods (NRs), $La_{10}Si_6O_{27}$ NPs, and Si^{2+} were shown to increase the contents of phenylalanine, salicylic acid, cinnamic acid, and p-coumaric acid—all associated with SAR activation—in rice by 17.4%, 11.4%, 35.9%, and 14.2%, respectively, while upregulating SAR-related genes to activate rice's immune responses [18]. Concurrently, Du et al. demonstrated that SiO_2 NPs enhance rice blast resistance against *P. oryzae* by inducing the expression of SA-related genes to activate SAR (Table 1) [25]. Beyond upregulating SA-dependent defense pathway genes (*OsICS*, *OsPAL*, and *OsWRKY45*), Wang et al. revealed that SiO_2 NPs can also activate ISR in rice by significantly increasing chemical barriers (total phenolics and proline) in leaves and upregulating JA biosynthesis genes (*OsPLD*, *OsLOX*, *OsOPR*) and signaling pathway gene *OsJAZ* [51].

In the model plant *Arabidopsis thaliana*, high concentrations of SiO_2 NPs triggered excessive silicic acid release, inducing either oxidative stress or severe stomatal blockage. While these effects attenuated the resistance-inducing capacity, they did not abolish it completely [52]. In contrast, Du et al. reported that 3000 mg/L SiO_2 NPs disrupted silicon uptake and caused abnormal accumulation in rice leaves, leading to dysregulated SA-responsive gene expression and, consequently, enhanced pathogen susceptibility. Therefore, for agricultural applications, SiO_2 NPs concentrations required careful optimization within a defined effective range.

3.2.2. Regulation of the Rice Antioxidant System

When plants are subjected to environmental stress stimuli, they initiate stress responses in which ROS stimulate the antioxidant defense system to mitigate oxidative damage [53]. However, excessive accumulation of ROS can induce membrane lipid peroxidation, damage cytochrome complexes, promote protein oxidation, and cause DNA strand breaks, leading to oxidative stress in plant cells. This results in the accumulation of malondialdehyde (MDA) and impairment of the antioxidant defense system, ultimately disrupting physiological and biochemical processes in plants [54,55]. Certain pathogens exploit excessive ROS accumulation in plants to induce oxidative damage to host cell membranes, thereby facilitating their colonization within host plants [56]. Consequently, NMs capable of scavenging ROS have been utilized to enhance crop stress resistance. Studies have demonstrated that various NMs, including CuO NPs, ZnO NPs, BNCs, and M-Cs NPs, induce disease resistance in rice by effectively scavenging intracellular ROS [37,56–58].

Under persistent oxidative stress, plants activated a series of antioxidant enzymes to neutralize destructive ROS and protected cells from oxidative damage [59]. Research demonstrated that NMs enhanced antioxidant enzyme activities and modulated disease resistance in rice. Specifically, $La_{10}Si_6O_{27}$ NRs, $La_{10}Si_6O_{27}$ NPs, and Si^{2+} ions upregulated

the expression of genes encoding antioxidant enzymes (CAT, POD, SOD, PAL) in rice infected with *R. solani* [18]. Selenium nanoparticles (Se^0 NMs) alleviated pathogen-induced oxidative stress by increasing glutathione peroxidase activity while reducing MDA levels associated with lipid peroxidation [60]. At a concentration of 8 μg/mL, molybdenum disulfide-copper nanoparticles (MoS_2-CuNPs) significantly decreased MDA content in rice plants while enhancing SOD, POD, and CAT activities by 54.08%, 31.70%, and 13.52%, respectively. In contrast, Cu NPs triggered ROS bursts in rice plants, leading to dose-dependent increases in MDA levels and antioxidant enzyme activities. Notably, the MoS_2-CuNP-induced elevation in antioxidant enzyme activities was dose-independent, indicating that this effect originated from the intrinsic properties of MoS_2-CuNPs rather than ROS generation [61].

3.3. Reinforcement of Physical Barriers

Silicon was absorbed by plants as monosilicic acid and subsequently polymerized into silica gel ($SiO_2 \cdot nH_2O$) through non-enzymatic reactions, depositing on plant leaves to form silica cells or papillae [62]. These silica structures reduced the digestibility of leaves and stems while enhancing their mechanical rigidity, thereby establishing physical barriers that improved plant disease resistance [63,64].

SiO_2 NMs were demonstrated to influence the biosynthesis pathways of cutin, suberin, and wax in cucumbers, while simultaneously increasing lignin content in rice roots, leaves, and stems, collectively enhancing physical defense mechanisms [51,65]. In rice leaves treated with SiO_2 NMs, dumbbell-shaped silica cells were observed aligned along leaf veins on the silicified epidermis, with both trichome quantity and density being significantly higher than those in control and sodium silicate (Na_2SiO_3) treatments.

Si NPs were found to form physical barriers on wheat leaf surfaces, with foliar application of 200 mg/L Si NPs resulting in a significant 27.7% reduction in lesion length [66]. These findings demonstrated that silicon-based NMs possessed considerable potential for enhancing rice disease resistance through physical barrier reinforcement.

However, it was observed that only a limited number of NMs exhibited the capacity to enhance physical barriers, while the underlying mechanisms remained largely unclear. Previous research had primarily focused on elucidating direct mechanisms, including the activation of endogenous resistance signaling pathways (e.g., SA/JA pathways) and regulation of antioxidant enzyme systems, whereas the role of NMs in reinforcing physical barriers received minimal attention.

3.4. Optimization of Pesticide Utilization Efficiency

Safe nano-encapsulation delivery systems were demonstrated to significantly enhance the chemical stability, dispersibility, and wettability of pesticides [67], while markedly reducing pesticide loss and endowing them with stimulus-responsive functionalities [68,69]. These systems enabled controlled enhancement of pesticide efficacy, thereby mitigating the adverse environmental impacts associated with conventional agricultural practices [70,71]. In recent years, the application of NMs in developing nano-pesticides has emerged as a research hotspot in the field of pesticide delivery, demonstrating significant potential for creating environmentally friendly pesticides with high efficiency, low toxicity, and intelligent responsive release properties.

NMs serving as drug delivery carriers were primarily classified into inorganic mesoporous nanomaterials, carbon-based nanomaterials, polymer-based nanomaterials, and metal/metal oxide nanomaterials (Figure 4). As pesticide carriers, these NMs facilitated targeted pesticide release [72]. Furthermore, through surface modification, nanocarriers were engineered to acquire stimulus-responsive controlled-release properties triggered by

environmental factors (pH, light, temperature, enzymes, etc.) and biological cues, allowing the on-demand release of active ingredients [73] and, consequently, enhancing pesticide utilization efficiency.

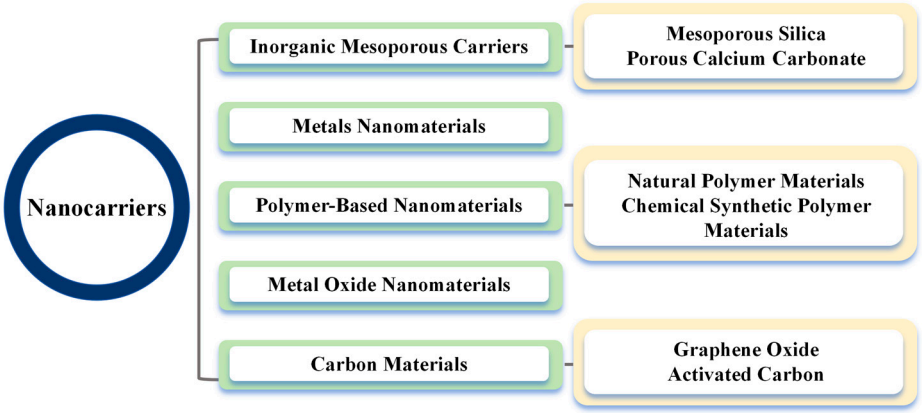


Figure 4. Major nanocarriers for drug delivery. These nanocarriers primarily include inorganic mesoporous carriers, carbon-based nanomaterials, polymer-based nanomaterials, and metal/metal oxide nanomaterials.

Pectin-coated nanocarriers with abundant functional groups were demonstrated to endow delivery systems with unique physicochemical properties, enabling targeted pesticide release while enhancing both safety and efficacy [74–76]. As an encapsulating agent, pectin (Pec) was found to confer the azoxystrobin (AZOX) delivery system (AZOX-AFS-Pec) with superior wettability, adhesion capacity, pH responsiveness, and enzyme responsiveness. Pectin modification significantly increased AZOX release to 46.6%, 55.4%, and 72.5% under pH 5.8, pH 8.0, and pectinase-containing conditions, respectively, over 204 h. Compared to AZOX SC, foliar application of 7.5 mg/L AZOX-AFS-Pec NPs markedly elevated SA and IAA levels, enhanced SOD and POD activities, and reduced the disease index in *R. solani*-infected rice plants (Table 1) [32]. Additionally, pectin modification was shown to improve pesticide absorption and translocation efficiency. Prochloraz (Pro)-loaded mesoporous silica nanoparticles (MSNs) modified with pectin were observed to penetrate rice roots and translocate the pesticide to all plant tissues. This composite nano-pesticide (Pro@MSN-Pec) exhibited 1.8-fold and 2.9-fold greater in vitro fungicidal activity against *M. oryzae* compared to conventional Pro EC and technical Pro, respectively [77].

Furthermore, modification with concanavalin A (Con A), a lectin protein exhibiting high affinity for *M. oryzae* spores, was reported to enhance the spore germination inhibition rate of the nano-pesticide GO-PEG-EPX by 2.4-fold, suppress leaf blast lesions, and significantly improve EPX's antifungal efficacy against rice blast. However, GO-PEG-EPX-Con A exhibited a higher EC_{50} (50% maximal inhibitory concentration) than GO-PEG-EPX, potentially because Con A might provide nitrogen nutrients for mycelial growth, thereby attenuating the synergistic effects between the nanocarrier and pesticide (Table 1) [29].

3.5. Regulation of Microbial Communities

When plants were disturbed by invasive pathogens, beneficial microbial communities were recruited from the environment through complex chemical pathways to resist pathogen infection [78]. NMs were demonstrated to induce disease resistance in rice plants by altering the activity, abundance, and diversity of beneficial microbial communities in the phyllosphere and rhizosphere [79].

Foliar application of BNCs significantly increased the total bacterial abundance in Xoo-infected rice plants. Compared to the control, rice plants treated with 250 mg/L BNCs showed 89.3%, 91.4%, and 89.7% increases in the Shannon, Simpson, and Pielou_e indices,

respectively, while the Chao1 index in leaf and root tissues was significantly enhanced by 80.3% and 9.9%, respectively (Table 1). In healthy rice plants, BNC treatment enhanced the relative abundance of beneficial microorganisms, including *Ochrobactrum*, *Allorhizobium*, *Mesorhizobium*, *Methylobacterium*, *Anaeromyxobacter*, *Massilia*, and *Devosia*, which were associated with nitrogen fixation, phosphate solubilization, phytohormone production, and plant growth promotion [37]. Foliar spraying of M-Cs NPs significantly increased the abundance of *Azonexus*, *Agarivorans*, and *Bradyrhizobium* in *M. oryzae*-infected rice leaves, as well as *Nitrospira* in the roots, which promoted nutrient uptake and soil nitrification. At the same time, Cu-Ag NPs increased the relative abundance of *Burkholderiales*, *Micrococcales*, and *Rhizobiales* in Xoo-infected rice plants [80]. However, these do not imply that NMs could only increase the abundance of certain microbial communities. M-Cs NPs significantly reduced ($p < 0.05$) the levels of *Batrachochytrium*, *Tulosesus*, and *Fusarium*, while the relative abundance of *M. oryzae* decreased by 93.5% [37].

However, few reports were available on how NMs affected soil functional microorganisms, with most studies focusing on their impact on microbial population diversity, leaving the question of whether NMs influenced soil health largely unexplored.

4. Conclusions

NMs are recognized as an emerging technology with tremendous potential for regulating rice disease resistance. This review systematically summarizes the mechanisms through which NMs enhance rice disease resistance (Figure 5). Specific NMs have been found to alter pathogen membrane permeability, penetrate microbial cells, and damage the structure and function of organelles, DNA, proteins, and lipids. By modifying intracellular signal transduction and generating ROS, NMs induce cellular apoptosis, demonstrating significant bactericidal and fungicidal activity. Certain NMs have been observed to form physical barriers on rice surfaces while simultaneously permeating leaf cells through stomatal openings. Following intracellular diffusion, ionic homeostasis and antioxidant systems within rice cells are effectively regulated. Moreover, SAR and ISR are activated in rice through SA and JA signaling pathways mediated by NMs. Furthermore, disease resistance is conferred through the modulation of microbial community structure in both the phyllosphere and rhizosphere, along with the efficient delivery of agrochemicals. These multifaceted functions collectively promote environmentally sustainable agricultural practices.

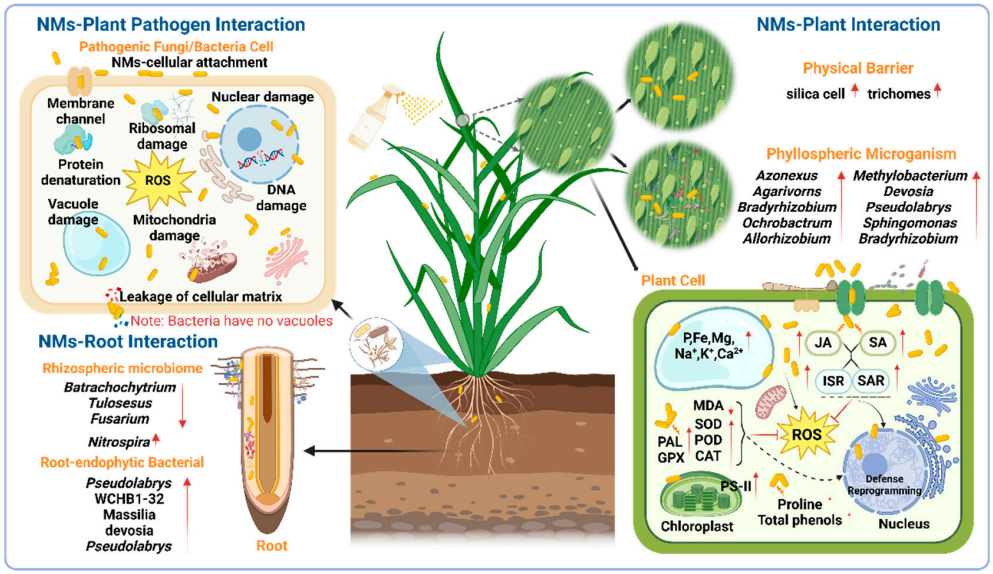


Figure 5. Mechanism model of NMs enhancing rice disease resistance. In leaf tissues, NMs exert dual-pathway effects: intracellular NMs activate ISR and SAR while regulating the antioxidant

defense system, whereas surface-retained NMs provide protection by reinforcing physical barriers and modulating functional microbial community structures. Within the root microenvironment, NMs enhanced disease resistance by reshaping rhizospheric and endophytic microbial compositions. For pathogens, organelle integrity was directly compromised by NMs, resulting in the leakage of genetic materials and proteins that effectively suppressed pathogen growth. Through these synergistic mechanisms, an integrated defense network was established, by which rice disease resistance was significantly elevated. Arrows indicate directional changes: ↑ for upregulation/increase, ↓ for downregulation/reduction. We created this figure using BioRender (created in BioRender. Yi, C. (2025) https://BioRender.com/o1zfxht (accessed on 29 June 2025)).

5. Future Prospects

5.1. Potential of NMs for Rice Genetic Modification

NMs have been demonstrated to serve as effective delivery vehicles for biomolecules, facilitating targeted genetic modifications in specific plant species [81]. When conjugated with specific ligands as nucleic acid carriers, NMs-based delivery systems exhibit broader applicability and higher efficiency compared to conventional biomolecular techniques, including agrobacterium-mediated transformation, gene gun bombardment, and electroporation [82,83]. To date, seven major types of nanocarriers have been employed for crop genetic modification: mesoporous silica nanoparticles (MSNs), polymeric nanoparticles, carbon nanotubes (CNTs), gold nanoparticles, magnetic nanoparticles, lipid nanoparticles, and layered double hydroxide nanosheets. Notably, MSNs have been successfully utilized to deliver pPZP122:35S:cryIAb-MSNs plasmids into tomato plants, achieving complete transcription and translation processes, which significantly enhance resistance against *Tuta absoluta* [84]. This MSNs-mediated transient genetic transformation demonstrates advantages such as good biocompatibility, time efficiency, and cost-effectiveness. CNTs have been found to enable the highly efficient delivery of intact plasmid DNA and facilitate high-level protein expression in non-model plants such as sesame, wheat, and cotton, without inducing transgenic integration [85]. In particular, chitosan-complexed single-walled CNTs have been reported to accomplish chloroplast-targeted transgene delivery and transient expression in mature plants of *Eruca sativa*, *Nasturtium officinale*, *Nicotiana tabacum*, *Spinacia oleracea*, and *isolated Arabidopsis* thaliana mesophyll protoplasts, without the need for gene guns or chemical assistance [86].

However, the application of NMs as gene vectors to enhance disease resistance in rice has not been reported. Given the superior delivery efficiency and expression performance demonstrated by NMs in other crops, future studies should focus on exploring their potential for genetic improvement of rice disease resistance.

5.2. Toxicological Effects of NMs

The beneficial effects of NMs were found to be directly dependent on specific factors including genotype/cultivar, morphology, size, dosage, composition, surface area, coating, redox state, application method, exposure duration, and growth substrate [87]. Certain NMs were demonstrated to exhibit potential toxicity to rice, the environment, and humans at particular concentrations. With the inevitable release of NMs into the environment, they were shown to be transported and accumulated in plant tissues, affecting physiological metabolism, posing potential threats to environmental organisms, and ultimately impacting human health through the food chain. These ecotoxicological effects have attracted increasing attention [88,89]. Studies by Samarajeewa et al. demonstrated that CuO NPs possessed high solubility and bioavailability in flooded paddy soils, exhibiting significant toxicity to soil microorganisms [90]. High concentrations of CuO NPs were observed to lead to excessive copper accumulation, lignification, and oxidative damage in rice, signifi-

cantly inhibiting seed germination and seedling growth [91]. Simultaneously, NMs were found to negatively affect soil microbial communities in rice paddies and interfere with fundamental soil functions, indirectly impacting rice growth and development [92]. WS_2 NMs at 100 mg/kg were reported to significantly reduce soil microbial diversity, increase MDA content in rice, and decrease total antioxidant capacity in leaves along with root biomass [93].

Current strategies to mitigate nanotoxicity were primarily based on exogenous application of NO, arbuscular mycorrhizal fungi, plant hormones, and melatonin (ME) [94–98], though their mechanisms were found to differ.

Their application introduces a complex duality characterized by both environmental benefits and ecological risks. While traditional pesticides face well-documented challenges such as bioaccumulation and non-target toxicity, NMs offer targeted delivery and reduced off-site movement—yet their novel risks remain less understood [73,99,100]. This inherent contradiction arises from their ability to improve crop protection more efficiently than conventional pesticides, while potentially accumulating in grains, disrupting soil ecosystems, or undergoing hazardous transformations in the environment. Thus, NMs are a promising supplement to integrated pest management rather than a standalone replacement at this stage. Addressing this paradox necessitates the integration of material innovation with safety controls, which include precision-designed biocompatible NMs, optimized application methods, and regulated degradation pathways—approaches rarely applied to traditional pesticide formulations. Concurrently, the establishment of international safety standards and rigorous assessment protocols is crucial to avoid repeating the historical regulatory delays seen with DDT and glyphosate. Future advancements depend on elucidating plant–NMs interactions and developing the next generation of safer NMs through a balanced risk–benefit evaluation that explicitly compares their lifecycle impacts with those of conventional agrochemicals.

5.3. Regulatory Frameworks for NMs

The efficacy of NMs in soil applications and the limitations of the associated regulatory frameworks continue to restrict their broader adoption [101]. Existing environmental risk assessment methodologies have faced significant scrutiny from the global scientific community, as they often fail to adequately address the unique properties and behaviors of NMs [102]. In 2019, the Global Summit on Regulatory Science (GSRS) emphasized the pressing need for coordinated regulatory frameworks to manage the emerging challenges posed by nanotechnology and NPs. The summit concluded with proposals for cross-agency collaboration and the establishment of an international working group to develop unified global guidance and standards, given the current lack of well-defined, harmonized approaches [103].

From regulatory and policy perspectives, many applications of nanotechnology remain in the early stages of development due to significant knowledge gaps in safety evaluations and commercialization challenges [103,104]. The central regulatory dilemma arises from technological innovations outpacing the development of regulatory frameworks, further complicated by the absence of global standards and inconsistent assessment methodologies [105]. Critical technical barriers include the complex physicochemical properties of NMs, such as size, shape, and surface characteristics, which influence toxicity but lack standardized characterization [106]. Additionally, there are insufficient safety assessment tools and emerging challenges. These issues are exacerbated by data transparency gaps, limited reference materials, and inadequate cross-sector coordination [107,108]. Therefore, international cooperation is essential to establish harmonized definitions, develop

advanced risk assessment tools, and implement transparent data-sharing mechanisms for effective governance of NMs.

5.4. Research Framework of the "NMs-Rice-Soil" Ternary System

Current research on the mechanisms by which NMs enhanced rice disease resistance was found to exhibit certain disciplinary limitations. NMs for enhancing rice disease resistance are predominantly conducted under in vitro and greenhouse conditions. While these controlled-environment studies contribute significantly to elucidating the fundamental mechanisms of NMs–pathogen–plant interactions, the practical efficacy of such applications under field conditions remains to be systematically evaluated due to multiple complex factors, including environmental variability, NP–soil interactions, and long-term stability issues.

On the other hand, most studies were focused on binary interaction models between plants and NMs. However, as the essential growth substrate for rice, soil was recognized not only to provide physical support and growing space but also to serve as a crucial environmental medium that sustained normal physiological metabolism, yield, and quality. The current research predominantly follows two isolated approaches: one examining direct nanoparticle effects on rice plants such as antimicrobial activity or immune induction, and another investigating nanoparticle behavior in soil environments including accumulation and transformation. These binary perspectives fail to account for critical system interactions, particularly how soil microbes may enhance nanoparticle functionality through processes like dissolution facilitation, while ignoring feedback mechanisms where nanoparticle-induced soil changes subsequently modify plant responses.

Nevertheless, investigations involving the "NMs-rice-soil" ternary system were largely confined to analyzing NMs environmental behaviors [109] and ecotoxicity assessments [110]. To overcome these limitations, our 'NMs-Rice-Soil' ternary framework introduces a comprehensive model that simultaneously captures horizontal nanoparticle–pathogen–plant interactions and vertical nanoparticle–soil microbiome–plant relationships. The indirect disease resistance mechanisms mediated by NMs through regulation of microbial community structure or metabolic behaviors were long considered to remain unexplored. This integrated approach enables quantitative analysis of multi-scale relationships, tracking how nanoparticle concentrations influence microbial community structure and ultimately affect systemic disease resistance.

Furthermore, it was acknowledged to be challenging to quantify the long-term ecological impacts of NMs on soil functions, particularly the correlation between microbial network stability and systemic resistance duration, as well as the spatiotemporal coupling relationships of their disease resistance effects. By unifying materials science, plant pathology and soil ecology perspectives, this framework provides a transformative foundation for developing sustainable crop protection strategies that account for real-world agricultural ecosystems.

Therefore, future research should prioritize the establishment of a three-dimensional "soil-plant-NMs" study system to facilitate the transition of NMs applications from laboratory research to field implementation. This transition is essential for advancing agricultural development and meeting global demands for more effective and environmentally conscious farming practices. The proposed core implementation pathways include:

1. Targeted coupling of functionalized NMs with rhizosphere probiotics, combined with metagenomics, time-resolved metabolomics, and spatially resolved proteomics. This approach aims to achieve cross-scale analysis of material–information flows and quantitative characterization of dose–effect relationships in NMs-mediated microbial metabolic remodeling and host resistance signaling.

2. An increased focus on NMs ecotoxicology research, utilizing machine learning models to predict critical disturbance thresholds of soil microbial networks under NMs' exposure. This effort will help establish early warning indicators and corresponding regulatory frameworks for the ecologically safe application of nano-agricultural technologies.
3. The development of multifunctional NMs for rice must be coupled with standardized field application and comprehensive evaluation systems to effectively translate laboratory research into practical agricultural applications. This combined approach is essential for realizing the full potential of nanotechnology in sustainable rice production.

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