Masudulla Khan
Jen-Tsung Chen *Editors*

Nanoparticles in Plant Biotic Stress Management

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Editors
Masudulla Khan
Department of Botany
Aligarh Muslim University
Aligarh, India

Jen-Tsung Chen
Department of Life Sciences
National University of Kaohsiung
Kaohsiung, Taiwan

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Dedicated to my beloved parents
Mr. Zaffar Ullah Khan
Mrs. Fatima Begum

Preface

Over the decades, the world has continued to face critical issues of an increasing human population and climate change, which threaten food security globally, and fortunately, new technologies based on the topic of plant sciences are upgraded fast and expected to overcome the crisis through the enhancement of agricultural production. Among these technologies, engineered nanomaterials/nanoparticles and associated emerging plant nanotechnology have been proven to have promising advantages when applied to a range of management in agriculture.

Each year, a huge loss in agricultural production can be caused by plant diseases that consequently damage global food security. However, the management of most diseases in crops remains a challenging task, and therefore, over the years, crop protection has been considered one of the most crucial research fields of plant sciences. In addition, when faced with global climate change, particularly the rising temperature, the negative impact of plant diseases can be more serious. Therefore, there is a high demand to organize strategies to make crops climate smart or resilient. In recent years, plant nanotechnology has gotten increasing attention on its remarkable potential to be applied in crop protection for releasing the potential of defense machinery and subsequently alleviating biotic stress caused by diverse pests and pathogens in the scenario of climate change.

This book collects a series of summaries organized by experts in nanotechnology to provide a systematic literature review and comprehensive discussion on the potential of nanomaterials/nanoparticles in combating plant biotic stress caused by bacteria, fungi, viruses, pests, pathogens, etc. The leading chapter presents fundamental and advanced methods for the management of crop diseases and then introduces a range of applications using nanomaterials in detecting diseases, targeted delivering pesticides, and enhancing tolerance to diseases. The following chapters provide insights into the molecular and physiological interactions involving phytohormones and cell signaling networks of some critical types of nanoparticles including AgNPs, MgO, SiO_2, and ZnO with plants and discuss their roles in disease management and accompanying issues of biosafety and phytotoxic behavior of nanomaterials, particularly at the stages of seed germination, vegetative growth, and fruit set.

The integration of green chemistry into plant nanotechnology gives considerable advances in the process of synthesis to produce a range of green synthesis nanoparticles using metallic and metalloid materials, which may ensure a more eco-friendly nanotechnology with biocompatible and biodegradable properties when applied in the sustainable management of plant diseases. Additionally, researchers have developed strategies based on the application of natural antimicrobials such as secondary metabolites, peptides, and enzymes that are encapsulated in stable, controlled-release organic-based nanoparticles in sustainably combating plant biotic stress. In brief, these achievements through the use of engineered nanoparticles as beneficial agents, elicitors, or carriers can highly support smart and sustainable agriculture in the future.

Based on the intensive exploration of literature, this book provides an in-depth analysis of the interaction of nanoparticles with crops when faced with major biotic stressors either under field conditions or in in vitro clonal propagation. For instance, seed priming and spraying using zinc oxide and copper oxide nanoparticles were found to be effective in the mitigation of plant diseases caused by significant species of bacteria, fungi, and parasitic nematodes. Interestingly, a frontier achievement is to use carbon-based nanomaterials such as graphene oxide not only to promote plant growth and alter plant metabolisms but also to induce immunity for better plant health under the attack of pathogens.

By providing a complete set of methods and applications using nanoparticles for the sustainable management of plant diseases, this book supports the UN's Sustainable Development Goals (SDGs), particularly, SDG2: Zero Hunger, which aims to end hunger and achieve food security for all. Undoubtedly, this book is an ideal reference for students and young scientists to quickly overview such a critical topic and for researchers, professors, and experts to efficiently gain summaries of each subtopic in plant nanotechnology with an emphasis on biotic stress management. Not only for plant pathologists, this book also provides valuable information for cross-field scientists, including the research fields of plant physiology, plant cell biology, plant molecular biology, plant biochemistry, plant biotechnology, plant tissue culture, plant stress, materials science and engineering, green chemistry, applied microbiology, and so on. As book editors, we would like to thank all the contributors for their insightful chapters. During the period of book organizing, the instruction and timely assistance from the publisher are very grateful.

Aligarh, Uttar Pradesh, India — Masudulla Khan
Kaohsiung, Taiwan — Jen-Tsung Chen

Acknowledgements

The current book, "Nanoparticles in Plant Biotic Stress Management," was developed to offer a one-pot remedy for controlling plant diseases brought on by pathogens and pests. As a result, most of the chapters were drawn from the works of erudite scientists, researchers, and academics to create a worthwhile and educational book. This book provides a quick overview of the various nanomaterials' roles in the sustainable management of plant diseases caused by pathogens and plant parasitic nematodes. As a result, the chapters have been created to ensure that consistency and coherence are maintained throughout and that the researchers have access to the most information possible on this subject. The most recent information regarding the management of plant diseases by the use of different nanomaterials has been compiled.

Furthermore, the Editorial Board would like to express its sincere gratitude to all of the authors for their contribution in this book. Without their help, this book would have remained the editors' vision alone.

Furthermore, editors extend hearty thanks to our beloved Prof. Mohammad Gulrez, Hon'ble Vice Chancellor, Aligarh Muslim University, and Prof. Naima Khatoon, Principal, Women's College, Aligarh Muslim University, Aligarh for being a source of inspiration.

I would like to express heartfelt gratitude to my thesis supervisor, Prof. Zaki Anwar Siddiqui for his guidance. Prof. Moinuddin, Dr. Fauzia Maushin, Dr. Amir Raina and Dr. Anushi A. Jahan of Women's College, Aligarh Muslim University, Aligarh, India, receive special thanks for providing critical suggestion.

I, Dr. Masudulla Khan would like to extend my deepest and heartfelt gratitude to my wife Dr. Aiman Parveen for her support.

I shall be failing in my duty if I don't thank my lovely family members K.U. Khan, A.U. Khan, M.U. Khan, S.U. Khan, Tanveer, Masarrat, Mohsina, Shazia, Shaista, Hiba, Saad, Ahmad, Sara for their selfless affection and motivation.

Without the unending help, prayers, and encouragement of their elders and youth in both happy and sad times, the editors could not have finished this endeavor. We hope that our attempts to guide readers toward a higher level of plant science will be successful.

Aligarh, Uttar Pradesh, India Masudulla Khan

Contents

Chapter 1
Nanomaterials for the Management of Crop Diseases: Methods and Applications

Manoharan Rajesh, Kempanna Sushmitha, Ganesan Megha, Ravichandran Sneha, Arockia Doss Cible, Mani Manoj, Manavalan Murugan, and Arumugam Vijaya Anand

Abstract Nanotechnology has emerged as a promising avenue for revolutionizing crop disease management. Nanomaterials have become a promising tool for the management of diseases in crops, offering innovative solutions to combat various agricultural challenges. This chapter provides an overview of the methods and applications of nanomaterials in crop disease management. The methods encompass the synthesis, characterization, and functionalization of nanomaterials tailored for specific crop diseases. Nanomaterials, due to their unique properties, offer innovative solutions for disease control in crops including nanoparticles and nanocomposites, with an emphasis on eco-friendly approaches. Additionally, we discuss the application of nanomaterials in disease detection, targeted delivery of pesticides, and enhancing plant resistance mechanisms. The potential benefits, challenges, and environmental implications of nanomaterial use in agriculture are also explored. This abstract highlights the significant strides made in harnessing nanotechnology for sustainable crop protection and disease management, shedding light on its potential to revolutionize modern agriculture.

Keywords Nanomaterials · Crop disease resistance · Crop disease protection · Crop disease control · Crop disease management · Sustainable agriculture

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M. Rajesh (✉) · K. Sushmitha · G. Megha
Department of Biochemistry, Bharathiar University, Coimbatore, Tamil Nadu, India

R. Sneha · A. D. Cible · M. Manoj · A. V. Anand
Medical Genetics and Epigenetics Laboratory, Department of Human Genetics and Molecular Biology, Bharathiar University, Coimbatore, Tamil Nadu, India

M. Murugan
Department of Biomedical Engineering, Noorul Islam Centre for Higher Education, Noorul Islam College of Engineering, Kanyakumari, Tamil Nadu, India

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1.1 Small Wonders, Big Impact: Nano-biosensors in Crop Disease Management

Nanotechnology is an emerging technology that has applications in many industries, including health (Anand et al. 2021; Rengarajan et al. 2022; Varalakshmi et al. 2022; Gunasangkaran et al. 2022), food safety and packaging (Pushparaj et al. 2022), agriculture and green synthesis (Jaison et al. 2023; Pushparaj et al. 2023), and other applications (Pavithran et al. 2020; Vadivelu et al. 2020). Nanotechnology has its roots in the discipline of material science. This technology has the potential to replace conventional medical treatment procedures, albeit further research is necessary before drawing definitive conclusions. Although nanoparticles can be produced chemically or physically, they prefer green synthesis, which makes use of plants, algae, and other organisms to manufacture nanoparticles that can be used in a range of fields (Thomas et al. 2022; Muthukrishnan et al. 2022; Srimurugan et al. 2022; Paramasivam et al. 2023).

Nano-biosensors, the intersection of nanotechnology and biotechnology, represent a groundbreaking advancement in the field of sensor technology. This technology offers a new dimension in plant disease diagnostic systems by providing non-destructive, minimally invasive, economical, and easy-to-use systems with improved detection limit, sensitivity, specificity, and in situ detection of plant pathogens (Kashyap et al. 2019). A nanosensor is a device with at least one nanoscale dimension that modulates a signal when it senses nanoscale objects or events. Nanosensors can operate independently or as active components of a large device. Nanosensors have been around for just over a decade, but their utility has already been demonstrated in industries as diverse as home security, medical, imaging, food marketing, environmental protection, and many others (Mahbub and Hoque 2020).

The journey of nanosensor evolution unfolds through history, starting with mechanical sensors in 1994, followed by an optical breakthrough in 1996 and optical fiber in 1998. Polymer beads and nanoelectrodes appeared in 1999, while variations appeared in the 2000s. The following years brought photonic explorers for biomedical use with biologically localized embedding, quantum dot, ion channel, and nano-strip sensors by 2002. By 2004, nanogap nanoparticles, magnetic nanoparticles, and Förster resonance energy transfer-based methods were in use. In 2005, advances were made in semiconductor, piezoelectric, and DNA sensors and localized surface plasmon resonance. Nanofiber sensors have marked a transformative period and are revolutionizing the properties of nanosensors (Lim and Ramakrishna 2006).

These nano-biosensors designed for disease detection in plants operate through the integration of biological recognition elements and nanomaterial transducers. These sensors play a pivotal role in identifying the presence of specific molecules closely linked with plant pathogens. The mechanism involves a series of intricate steps: Firstly, a bio-recognition element, which could be antibodies, enzymes, or nucleic acids, is employed. This element selectively binds to target molecules produced by the pathogens responsible for plant diseases. Secondly, nanomaterials such as carbon nanotubes or nanoparticles act as transducers. When the bio-recognition element interacts with the target molecule, it sets off a cascade of events leading to discernible alterations in the nanomaterial's characteristics. These changes manifest as modifications in electrical conductivity or optical properties, which constitute detectable signals. To amplify the sensitivity of detection, many nano-biosensors incorporate signal amplification strategies. Enzyme-catalyzed reactions or techniques harnessing surface plasmon resonance are often utilized for this purpose. The generated signal is then transduced into a readable format—for instance, electrical changes are quantified, while optical sensors might detect shifts in fluorescence intensity or color. This transduced signal subsequently undergoes thorough analysis, translating it into meaningful data. This critical information is meticulously assessed to deduce both the presence and concentration of the target pathogen. This streamlined process enables nano-biosensors to provide high sensitivity, swift detection, and real-time monitoring capabilities. These sensors can be conveniently deployed directly in the field, ushering in early detection and enabling prompt interventions to curtail further pathogenic proliferation. Figure 1.1 highlights the mechanism of nano-biosensors for identifying plant disease.

The below classification helps us identify the best nano-biosensor design for particular disease detection applications by taking into account elements like sensitivity, selectivity, usability, and compatibility with clinical settings (Fig. 1.2).

Utilizing nanosensors, the agricultural industry may benefit from the capabilities of nanotechnology. It can enhance disease control and therapy and enrich comprehension of host-parasite molecular associations. The detection of diverse pathogens, fertilizers, and soil moisture levels is also possible through nano-biosensors. By utilizing this technology, crop protection products can be reduced, nutrient loss can be lessened, and optimal nutrient management practices can allow for an increase in yield (Kaushal and Wani 2017).

Incorporating novel nanomaterials enhances the existing biochemical assays or bioassays and provides substantial improvement in sensitivity and selectivity. Meanwhile, rapid and site diagnosis of plant diseases has been facilitated, particularly in resource-deprived settings, by nanostructure-supportive non-invasive detection tools coupled with mobile visual equipment, e.g., smartphones, while long-term

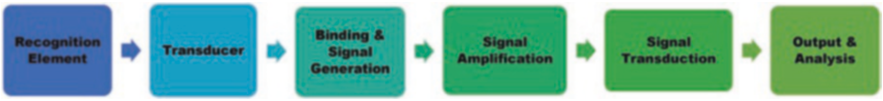

Fig. 1.1 Mechanism of nano-biosensors for recognizing plant diseases

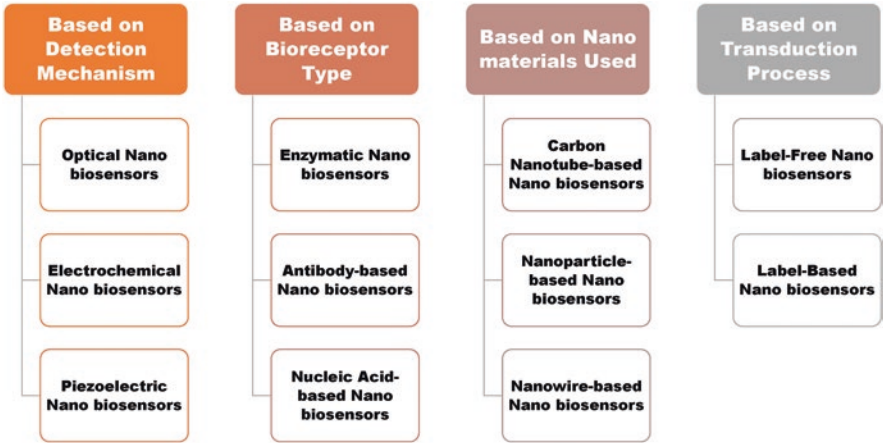

Fig. 1.2 Classification of nano-biosensors

monitoring of plant health conditions is made possible through a system of nanostructure-enabled non-invasive devices (Li et al. 2020). Sensors find application in agriculture encompassing areas like heavy metal ions, pollutants, microorganism load, and pathogens as well as the quickness with which temperature, traceability, or humidity is monitored is one of the application areas for sensors in agriculture (Johnson et al. 2021).

The application of nano-biosensors in plant disease detection is extremely promising in the future (Table 1.1). These sophisticated sensors have the potential to revolutionize agriculture by providing real-time, highly sensitive monitoring of plant health. It may detect pathogens at the molecular level by combining nanotechnology and biological identification elements, allowing for early and accurate illness diagnosis. This proactive strategy can result in more successful disease management techniques, more efficient use of resources such as pesticides and fertilizers, and higher crop yields. Nano-biosensors have the potential to greatly minimize economic losses and environmental problems associated with plant diseases by giving farmers timely information about the health of their plants, thus playing a critical role in guaranteeing global food security.

Table 1.1 Fabrication of biosensors for different pathogens

S. no.	Constituents of nano-biosensors	Sensor fabrication	Against pathogen	Detection mechanism	Sensitivity	Sample type	References
1.	Silicon nanoparticles (Rubpy-IgG)	Surface immunological functionalization	*Xanthomonas campestris*	Fluorescence quenching	7.5 ng	Cruciferous vegetables	Mondal and Jain (2021)
2.	Gold nanoparticles (ssDNA)	Surface functionalization	*Ralstonia solanacearum*	Colorimetry	25 µg/mL	Tomato, pepper, eggplant, and Irish potato	Mondal and Jain (2021)
3.	Gold nanoparticles	Surface functionalization	Aflatoxins	Surface-enhanced Raman scattering	5 × 10^{-5} M for aflatoxin B1 ~ 10^2 cfu	Maize, peanuts	Li et al. (2020)
4.	Cadmium quantum dots	Surface immunological functionalization	*Citrus tristeza*	Förster resonance energy transfer	220 ng/mL	Citrus trees	Li et al. (2020)
5.	Cadmium quantum dots (Rdk)	Surface immunological functionalization	*Citrus tristeza*	Förster resonance energy transfer	35–62 nM	Citrus trees	Li et al. (2020)
6.	Titanium dioxide nanotubes	Surface functionalization	Aflatoxin B_1 on acetylcholinesterase activity	Amperometric analysis using conventional three-electrode cell	0.33 nM	Detection of aflatoxins	Yuan et al. (2018)
7.	Gold nanoparticles (ssDNA)	Nanoparticle functionalization and DNA hybridization	*Ralstonia solanacearum*	Colorimetric detection	25 ng	Potato	Khaledian et al. (2017)
8.	Gold nanoparticles (ssDNA)	Nanoparticle functionalization and DNA hybridization	*Pseudomonas syringae*	Electrochemistry	214 pM	*Arabidopsis thaliana*	Lau et al. (2017)
9.	*Cadmium selenide* (polyethyleneimine quantum dots)	Surface functionalization	*Trichoplusia ni*	Fluorescence	pH range of 2.13–9.34	*Arabidopsis thaliana*	Koo et al. (2015)
10.	Carbon dots	Surface functionalization	*Fusarium avenaceum*	Fluorescence	50 nM	*Punica granatum*	Kasibabu et al. (2015)

(continued)

Table 1.1 (continued)

S. no.	Constituents of nano-biosensors	Sensor fabrication	Against pathogen	Detection mechanism	Sensitivity	Sample type	References
11.	Gold nanoparticles (ssDNA)	Nanoparticle functionalization and DNA hybridization	*Phytophthora ramorum* and *Phytophthora lateralis*	Surface-enhanced Raman scattering	N/A	Rhododendron leaves	Yüksel et al. (2015)
12.	Zinc oxide nanoparticles (chitosan nanocomposite membrane)	Single-stranded DNA probe	*Trichoderma harzianum*	Electrochemistry	1.0×10^{-19} mol/L	Detection of fungus in soil	Siddiquee et al. (2014)
13.	Gold nanoparticles	Immunosensor	*Pantoea stewartii*	Enzyme-linked immunosorbent assay	7.8×10^{-3} cfu/mL	Corn seed soak	Zhao et al. (2014)
14.	Titanium dioxide and stannic oxide nanoparticles	Surface functionalization	*p*-Ethylguaiacol	Electrochemistry	0.5 ppm	Strawberries	Fang et al. (2014)
15.	Gold nanorod	Antibody-functionalized gold nanorod Fiber optic particle plasmon resonance sensor	*Cymbidium mosaic virus* and *Odontoglossum ringspot virus*	Fiber optic particle plasmon resonance	4.8×10^{11} g/mL (*Cymbidium mosaic virus*) 4.2×10^{11} g/mL (*Odontoglossum ringspot virus*)	Orchids	Lin et al. (2014)
16.	Quantum dots	Surface functionalization DNA probe	*Ganoderma boninense*	Fluorescence resonance energy transfer	3.55×10^{-9} M	Oil palm	Mohd Bakhori et al. (2013)
17.	Cadmium-telluride quantum dots	Surface immunological functionalization	*Phytoplasma aurantifolia*	Fluorescence	5 *Ca. P. aurantifolia*/μL	Lime trees	Rad et al. (2012)
18.	Polypyrrole nanoribbon	Surface immunological functionalization	Cucumber mosaic virus	Lithographically patterned nanowire electrodeposition	10 ng/mL	Cucumbers	Chartuprayoon et al. (2013)

1.2 Precision Pest Control: Nanopesticides and Nano-insecticides Leading the Way in Crop Disease Mitigation

Globally, plant disease poses a significant obstacle for agriculturists in crop production, leading to estimated annual losses of 30–40% (Flood 2010). Various chemical choices are employed in agriculture to prevent plant diseases. While these chemicals offer advantages, they can also have detrimental effects on beneficial organisms that aid plants and pose risks to human health. So, in the quest for more potent and eco-friendly pest control solutions, integrating nanotechnology and agriculture has given rise to nano-insecticides and nanopesticides. Both of these have undoubtedly spurred innovation in the agriculture field. By exploiting the unique properties of nanoparticles, both of these aim to address some of the obstructions associated with traditional conventional pesticides, ushering in a new era of sustainable pest management with minimal or no harm to the environment (Wang et al. 2022).

The need for a shift from conventional pesticides and insecticides to nanotechnology-incorporated strategy is the need for this hour because of the risks it poses for both human health and non-target organisms. But nanopesticides and nano-insecticides, on the other hand, align with the pursuit of sustainable and secure agricultural practices. Also, they resist pests and insects by delivering the active compounds with heightened efficiency by controlled release with the application of lower doses itself, thereby fostering a more resource-efficient approach (Kumari et al. 2020). Nanotechnology is being driven in the pesticide industry by the need to decrease the amount of pesticides needed for crop protection. This is achieved by enhancing solubility, controlled release, precise delivery, better sticking ability, improved effectiveness and stability of active ingredients in the environment (Kah et al. 2018). They have the potential to take on various formulations such as emulsions, suspensions, polymer sheets, and gels. Alternatively, they can serve as capsules constructed from materials like silica, chitosan, sodium alginate, or polyethylene glycol (PEG) for encapsulating chemical substances (Shahzad and Manzoor 2021).

In 1997, a study explored the potential of nanospheres to enhance the transportation of a novel insecticide to plants. While nanosphere formulations exhibited reduced speed and release compared to a reference, their diminutive size led to enhanced penetration and systemic distribution of the insecticide within plants, despite the absence of controlled release (Boehm et al. 2003). Nanopesticides can be manufactured using two methods: (1) creating pesticides directly on the nanoscale and (2) loading the active pesticide components into nanocarriers. There are two main types of nanopesticides. The first type includes nanopesticides made from metals like silver, copper, and titanium. These have nanoparticles of the metal as the active ingredient without any carriers. The second type involves nanopesticides where the active ingredients are enclosed in nanocarriers such as polymers, clays, zein nanoparticles, or in the form of emulsions or liposomes (Kannan et al. 2023).

Efficient methods to address pest issues have been discovered through the utilization of nanoparticles. Imidacloprid-loaded sodium alginate nanoparticles controlled leafhoppers (Kumar et al. 2014). Nanogels composed of chitosan and cashew gum incorporating *Lippia sidoides* oil were made that demonstrated to have effective larvicide efficacy through slow, sustained release with optimized formulations (Abreu et al. 2012). PEGylated acephate nanoparticles acted as an alternative pesticide against *Spodoptera litura*. Lambda-cyhalothrin/silver nanoparticles were 37 times more efficient against *Spodoptera littoralis*. Novaluron nanoparticles caused 92% mortality in *Spodoptera littoralis*. Silver nanoparticles were effective against *Heterodera sacchari*. Nanocalcium protected crops from *Aonidiella aurantii* and *Bactrocera dorsalis*. Diacetyl hydrazine-based nanoformulations had potent anti-pest effects on *Spodoptera litura*. An emulsion cross-linking method was employed to produce sodium alginate nanoparticles loaded with imidacloprid. These nanoparticles demonstrated their ability to effectively combat sucking pests, particularly leafhoppers, displaying insecticidal properties (Kannan et al. 2023). In the forthcoming years, utilizing nanopesticides and nano-insecticides on estuarine plants can be studied, given their pronounced utility. Further research on environmental fate is required, alongside policy development, outreach to farmers, and innovation of new formulations with standardized protocols to foster a greater embrace of nano-empowered agriculture (Table 1.2).

Table 1.2 Synthesis of nanopesticides against different pathogens

S. no.	Nanoparticles	Against pest/ insect	Host	Impact	References
1.	Metal organic PCN-777 nanoparticles with avermectin	*Spodoptera litura*	Cabbage	Significant effectiveness in managing indoor insect populations and achieving successful control of pests in field conditions, coupled with the intelligent and responsive manner of releasing the pesticide	Liu et al. (2023)
2.	Nano-suspensions using leaves extracts of *Azadirachta indica* and flowers extracts of *Chrysanthemum coronarium*	*Tribolium castaneum* and *Rhyzopertha dominica*	Stored products	Both pests experienced a complete mortality rate of 100% when both plant extracts and its corresponding nano-suspensions were used at 100% concentrations. However, this combination with led to a greatest mortality rate of 100% in just 72 h	Hazafa et al. (2022)

(continued)

Table 1.2 (continued)

S. no.	Nanoparticles	Against pest/ insect	Host	Impact	References
3.	Neem oil-based nano-emulsion with natural adjuvant (*Prosopis juliflora* and *Cymbopogon citratus*)	*Bemisia tabaci*	*Solanum melongena*	Reduced levels of pesticide residues and the inclusion of natural adjuvants enhanced both the reliability and effectiveness of these biopesticides	Iqbal et al. (2022)
4.	Silica nanoparticles	*Fusarium oxysporum* f. sp. *niveum*	*Citrullus lanatus*	Enhanced plant growth, disease suppression (*fusarium* wilt disease) and remarkably increased fruit yield	Kang et al. (2021)
5.	Copper oxide nanoparticles	*Fusarium oxysporum* f. sp. chrysanthemi	Chrysanthemum	Increased average dry biomass and reduced disease severity	Elmer et al. (2021)
6.	Silver nanoparticles	*Meloidogyne incognita*	*Solanum nigrum*	Abnormalities include distorted embryonic development (tadpole stage), excessive growth, irregular division (gastrula stage), distinct endoderm-ectoderm cell variations, and noticeable paralyzed larvae	Fouda et al. (2020)
7.	Silver nanoparticles	*Meloidogyne graminicola*	*Oryza sativa*	Dose-dependent effectiveness in significantly reducing root gallings; progressively decreased galling as doses increased	Baronia et al. (2020)
8.	Copper nanoparticles and zinc nanoparticles	*Botrytis cinerea* and *Colletotrichum* spp.	*Prunus domestica*	Restrained fungal mycelial expansion, demonstrating potential variations in their mechanism, displayed escalated toxicity during spore germination	Malandrakis et al. (2019)

(continued)

Table 1.2 (continued)

S. no.	Nanoparticles	Against pest/insect	Host	Impact	References
9.	$Cu_3(PO_4)_2 \cdot 3H_2O$ nanosheets	*Fusarium oxysporum* f. sp. *niveum*	*Citrullus lanatus*	Notable disease suppression effects and potential yield improvements	Borgatta et al. (2018)
10.	Citrus peel essential oil nanoformulation	*Tuta absoluta*	Tomato	Eggs experienced a postponed impact, decrease in the count of larvae that successfully developed into adults, disturbing influence on insect development	Campolo et al. (2017)
11.	Nanostructured alumina	*Sitophilus oryzae*	Stored products	Charged nanoparticles adhere to the insect's outer layer via triboelectric forces, absorbing its wax covering and causing dehydration. Additionally, ingesting these nanoparticles increased mortality in the affected insects	Stadler et al. (2017)
12.	Mesoporous alumina nanoparticles	*Fusarium oxysporum*	Tomato	Increased growth parameters by around twofold, reduced damage from root rot, and enhanced photosynthesis process	Shenashen et al. (2017)
13.	Green silver nanoparticles	*Meloidogyne javanica*	*Solanum melongena*	Reduced the population of *Meloidogyne javanica* second-stage juveniles in soil; beneficial effects on the growth and alterations in the DNA profile	Abdellatif et al. (2016)

(continued)

Table 1.2 (continued)

S. no.	Nanoparticles	Against pest/ insect	Host	Impact	References
14.	Silica nanoparticles	*Callosobruchus maculatus*	Pulse seeds of *Macrotyloma uniflorum*, *Vigna radiata*, *Cajanus cajan*, *Vigna mungo*, *Vigna unguiculata*, and *Cicer arietinum*	Notable decrease in egg laying; damaged cuticles, lead to water loss, dehydration, and insect mortality	Arumugam et al. (2016)
15.	Titanium dioxide nanoparticles and zinc oxide nanoparticles	*Agrius convolvuli*	Sweet potato leaf powder	Reduced both testis weight and sperm bundle count; led to nanoparticle-triggered vacuoles impacting chromatin condensation; harmful effects on insect spermatogenesis	Kubo-Irie et al. (2015)
16.	Myristic acid-chitosan nanogels encumbered with *Cuminum cyminum* essential oil	*Sitophilus granarius* and *Tribolium confusum*	Stored products	54% *Sitophilus granarius* mortality occurred in 10 days, while *Tribolium confusum* showed 54% mortality after 20 days of storage	Ziaee et al. (2014)
17.	Pyridalyl nanocapsule suspension	*Helicoverpa armigera*	Tomato fruit	Facilitated penetration of nanoparticles via the digestive tracts' epithelial lining and enhanced access to capillaries, encouraging widespread circulation; modifies protein tertiary structure, resulting in impaired function and eventual demise of the insect	Saini et al. (2014)

(continued)

Table 1.2 (continued)

S. no.	Nanoparticles	Against pest/ insect	Host	Impact	References
18.	Copper nanoparticles	*Phytophthora infestans*	*Lycopersicon esculentum*	Demonstrated greater efficacy than commercial agrochemicals, with no plant-harming effects	Giannousi et al. (2013)
19.	Nanogel of methyl eugenol pheromone	*Bactrocera dorsalis* Hendel	*Psidium guajava*	Highest trap catches occurred in the initial 3 weeks; yielded abundant harvest and crops without any damage; a positive safety record, rendering it highly suitable for controlling pests across various types of crops	Bhagat et al. (2013)
20.	Zinc oxide nanoparticles	*Botrytis cinerea* and *Penicillium expansum*	*Botrytis cinerea* (table grapes) *Penicillium expansum* (stored apples and pears)	Elevated nucleic acid and carbohydrate bands in *Botrytis cinerea*, signifying altered cell functions and stress response, and decreased bands related to carbohydrates, lipids, and proteins, resulting in complete inhibition of fungal growth found by Raman spectroscopy	He et al. (2011)

1.3 Different Types of Nanomaterials Used for Crop Protection

The population has increased by more than four times over the last century. An agricultural food supply for an unprecedentedly growing population exacerbates the situation (Habeeba 2022). Moreover, plant diseases and pests considerably reduce crop output, with annual losses estimated to be between 20% and 40% on a global scale (Worrall et al. 2018). In addition to that, the establishment and spread of new pathogenic races are the constant problems because chemical pest management is expensive and ineffective. Researchers have recently proposed nanomaterials as a viable replacement for the current techniques of plant disease management and crop production (Malukani et al. 2021). Because they have properties that extend shelf life, increase the solubility of least-harmful and water-soluble pesticides, and improve site-specific penetration into the target insect. They protect crops by themselves and serve as a vehicle for insecticides (Hayles et al. 2017).

At the moment, there are numerous nanomaterials here, including metalloids, metallic oxide, non-metals, carbon nanomaterials, and functionalized dendrimer, liposome, and quantum dot forms (Elmer and White 2018). However, compared to humans, its application in disease control is less widespread in plants. Metal, metal oxide, and carbon nanoparticles were used in the majority of the studies (Li et al. 2018). The silver nanoparticles are highly reactive, effective in bactericidal and fungicidal effects, and efficiently penetrate microbial cells at lower concentrations, resulting in microbial control (Lamsa et al. 2011). For example, the accumulation of silver impairs respiration and metabolism while also generating reactive oxygen species (ROS), which results in damaged *Magnaporthe grisea*, which causes the rice blast illness in *Oryza sativa (*Akter 2019*)*.

Fungi toxicity experiments reveal that z*inc oxide nanoparticles* are more toxic to fungal species than $ZnSO_4$, while copper nanoparticles are more fungi-toxic than $CuSO_4$. Especially the silver *nanoparticles* suppress grey mold symptoms on plum fruit, inhibiting disease development by suppressing the symptoms of this disease (Malandrakis et al. 2019). When compared to bulk $CuSO_4$ and $MgSO_4$ treatments, copper oxide nanoparticles and magnesium oxide nanoparticles significantly decreased the incidence of brown rot disease to 71.2% and 69.4%, respectively. They improved enzyme productivity, chlorophyll content, and potato plant yield. Lipid peroxidation and ultrastructural studies revealed that nanomechanical forces severely harmed the bacterial cytomembrane (Rabea et al. 2023).

Silica is crucial for monocot plants, providing biotic and abiotic stress tolerance. It modulates host resistance to pathogens and is essential for silica nanoparticles to enhance plant resistance. Silica-mediated defense mechanisms against fungi increase phenolic compounds and enzymes like chitinases, peroxidases, and polyphenol oxidases (Suriyaprabha et al. 2014). Against infections like *Fusarium solani*, *Neofusicoccum* sp., and *Fusarium oxysporum*, copper nanoparticles have antifungal properties. The phytotoxicity of clove oil reduces the growth of maize seeds, while copper nanoparticles grafted with essential oils improve plant defense systems by directly disrupting pathogen membranes and perhaps preventing *Bipolaris maydis* leaf blight (Dorjee et al. 2023).

Chitosan, a natural polymer, has been shown to protect hosts from fungal infections, boost defense-related enzyme activity in *Arabidopsis* and tomatoes, and regulate β-1,3-glucanase and chitinase gene expression. However, its insolubility in aqueous media limits its widespread application with low antifungal properties. Chitosan's chelating property makes it a suitable biopolymer for improved stability, solubility, and antifungal activity (Sarkar et al. 2022). For instance, silver and chitosan-loaded salicylic acid stimulates secondary metabolites in the cassava plant to increase plant protection against leaf spot disease (Hoang et al. 2022). The blast illness was delayed, and the induction of ROS and peroxidase activity in the leaves was facilitated by the use of copper chitosan in finger millet (Sathiyabama and Manikandan 2016).

Fusarium graminearum and *Fusarium poae* are significantly inhibited by single-walled carbon nanotubes, multi-walled carbon nanotubes, fullerene (C_{60}), and reduced graphene oxide (Hao et al. 2017). Additionally, they combat the chlorotic yellow virus illness by reducing cucurbit chlorotic yellows virus symptoms and preventing viral replication (Al-Zaban et al. 2022). Few studies have been conducted using dendrimers as a carrier system and extracted essential oils. Hydrophobic substances have a common propensity to become less volatile when combined with polyamidoamine (PAMAM). PAMAMG4.0's abundant positively charged surface NH_2 groups make it easier to engage with and break down negatively charged microbial membranes. Oil/PAMAMG4.0 as a result completely interacts with the fungus cell membrane and easily penetrates the cell layer, killing fungi cells (Thanh et al. 2019).

When combined with protective agents, Cymoxanil (CYM) is a powerful therapeutic agent in agriculture. However, due to its great sensitivity and quick degradation, it cannot be used in fields. These problems are addressed, and efficacy is increased by using nanocarriers like liposomes. Due to their simple manufacture, monodisperse makeup, and biocompatibility, liposomes are well-researched nanocarriers for drug loading. However, due to stability concerns and oxidation/hydrolysis, traditional liposomes with phospholipids are not suited for agricultural uses. The formation of large unilamellar non-phospholipid liposomes with high specific surface area and stability in the aqueous phase holds a promise as potential drug carriers in agriculture (Zhang et al. 2021).

Graphene-copper atomic or nanometric materials complement each other, improving functions and properties and enhancing interrelation. By examining physiological and metabolic changes in response to biotic stress, graphene-copper nanocomposites and functionalized graphene nanomaterials can promote resistance to *Fusarium oxysporium f.sp. lycopersici* (Fol) and aid in the growth and development of tomato plants affected by the "vascular wilt" disease (Cota-Ungson et al. 2023). According to the findings, the graphene oxide-silver nanocomposite showed a nearly fourfold improvement over pure silver *nanoparticles* (Liang et al. 2017). Eugenol oil nanoemulsions are stable oil-in-water emulsions with broad-spectrum activity against viruses, fungi, and bacteria. They inhibit radial growth, sporulation, and pigmentation of pathogens while reducing mold growth and mycotoxins produced by mold. Studies have shown that eugenol alone can reduce mold growth and mycotoxin production (Abd-Elsalam and Khokhlov 2015).

Researchers face challenges in studying nanomaterials in different plant and disease systems, requiring separate studies for each. Chemists must develop innovative nanocomposites and formulations to combat hetero−/homo-aggregation and agglomeration. Nanotechnology's disease suppression tactics are crucial for global food security. Undoubtedly, in the upcoming years, the design and synthesis of multifunctional nanocomposites will be quite appealing. For instance, it is feasible to develop composites with antimicrobial activity that improve plant growth and activate the plant immune system by co-loading pesticides, micronutrients, and immune elicitors. This multimodal action mechanism may be detrimental to the emergence of pathogen resistance while also being highly efficient in the suppression of disease (Fu et al. 2020). Table 1.3 represents the different types of nanomaterials used against different kinds of pathogens.

Table 1.3 Different types of nanomaterials used against different pathogens

Type of nanomaterials		Name of crop	Disease	Pathogen	Effect of nanoparticles	Concentration	References
Metal	Silver nanoparticle	*Beta vulgaris*	Soft rot disease	*Pectobacterium carotovorum*	Direct penetration of silver into the cytoplasm of pathogen inactivated the enzyme that leads to cell death	100 ppm	Ghazy et al. (2021)
		Cucumber and pumpkin	Powdery mildew	*Golovinomyces cichoracearum* or *Sphaerotheca cusca*	Inhibit respiration and metabolism to cause physical damage of microbe and also intercalating the DNA prevent proliferation	100 ppm	Lamsa et al. (2011)
		Oryza sativa	Rice blast disease	*Magnaporthe grisea*	Accumulation of silver decreases the metabolism and respiration and also produces ROS that leads to cell damage	100 ppm	Akter (2019)
		Pepper	Pepper mild mold	Pepper mild mold virus	Increase the phenolic compound and build up the total soluble protein	400 µg/L	Elbeshehy et al. (2022)
		Banana (*Musa* sp.)	Banana bunchy top	Virus	Inducing the change in chlorophyll a and b and carotenoids and also reducing the replication of BBTV	50 ppm	Mahfouze et al. (2020)
	Essential oil-grafted copper nanoparticle	Maize	Maydis leaf blight	*Bipolaris maydis* and *Rhizoctonia solani* f. sp. *saskii*	Optimal concentration of nanoparticle inhibits the pathogen activity	500 mg/L	Dorjee et al. (2023)

Chitosan	Chitosan nanoparticle	Chilli	*Alternaria* leaf spot disease	Fungi	Inducing the different defense enzyme along with total flavonoid and phenol content	–	Sarkar et al. (2022)
	Chitosan-encumbered silver and salicylic acid	Cassava plant	Leaf spot	*Alternaria* sp.	One of the best methods to improve plant immunity is to stimulate the secondary metabolites	200–400 ppm	Hoang et al. (2022)
	Chitosan nanoparticle	*Solanum lycopersicum*	Wilt disease	*Fusarium. oxysporum* f. sp. *lycopersici*	Delaying the symptom of wilt disease	–	Sathiyabama and Charles (2015)
	Copper chitosan	Soybean	Bacterial pustule disease	*Xanthomonas axonopodis*	Inhibiting the growth of bacteria by increasing the concentration of copper	–	Swati and Joshi (2020)
		Finger millet	Blast disease	*Pyricularia grisea*	Delayed expression of blast symptoms by inducing the ROS and peroxidase in activity leaves	1 mg/mL	Sathiyabama and Manikandan (2016)
		Maize	Post-flowering stalk rot disease	*Fusarium verticillioides*	Inhibiting the various metabolic reaction by interaction with the surface area of fungi and bacteria	0.1% and 0.14%	(Choudhary et al. 2017)
	Chitosan nanoparticle	*Oryza sativa*	Sheath blight pathogen	*Rhizoctonia solani*	Activating the defense enzyme like peroxidase, phenylalanine ammonia lyase, and chitinase	–	Divya et al. (2020)
Beta D glucan nanoparticle	Beta D glucan nanoparticle	Turmeric crop	Rhizome rot disease	*Pythium aphanidermatum*	Rapid activation of various defense enzymes which is present in leaves and rhizome	–	Anusuya and Sathiyabama (2015)

(continued)

Table 1.3 (continued)

Type of nanomaterials		Name of crop	Disease	Pathogen	Effect of nanoparticles	Concentration	References
Metal oxide	Zinc oxide, copper oxide, silver nanoparticles	*Prunus domestica* fruit	Gray mold disease	*Botrytis cinerea*	Suppressing the symptom of gray mold disease	162 and 310 μg/mL	Malandrakis et al. (2019)
	Fabricated mesoporous alumina nanoparticle	*Solanum lycopersicum*	Tomato root rot disease	*Fusarium oxysporum*	Increase the surface-to-surface ratio, active surface site, and open channel pore	–	Shenashen et al. (2017)
	Magnesium oxide		Bacterial wilt disease	Tomato ralstonia	Through induced resistance	–	Imada et al. (2016)
	Copper oxide and magnesium oxide	*Solanum tuberosum*	Potato brown rot disease	*Ralstonia solanacearum*	Increasing the total chlorophyll content and enzyme efficiency	3 mg/mL	Rabea et al. (2023)
	Zinc oxide	Strawberry	Gray mold	*Botrytis cinerea*	Nanoparticle activated by UV, produce the ROS, and delayed the spoilage	–	Hashemi and Ahmadzadeh (2023)
		Coffee	*Erythricium salmonicolor* fungi caused by pink disease	*Erythricium salmonicolor*	Inhibit the fungal growth	6 mmol/L	Arciniegas-Grijalba et al. (2017)
	Copper oxide	*Cucumis sativus*	Root rot disease	*Fusarium solani*	Plasmolysis the mycelia as well as shrinking, collapsing the *Fusarium solani* and also increasing the activity of defense enzyme	–	Kamel et al. (2022)
	Zinc compound (zinc sulfate, $ZnSO_4$, and zinc oxide)	*Triticum aestivum*	Fusarium head blight	*Fusarium graminearum*	Reducing fungi and deoxynivalenol by using lower concentration of zinc oxide nanoparticle	100 mM	Savi et al. (2015)
Non-metal	Nano silica	Maize	Stem and ear root disease	*Fusarium oxysporum*, *Aspergillus niger*	Enhance accumulation of phenolic compound and defense enzyme like chitinase and peroxidase	10 kg/ha	Suriyaprabha et al. (2014)