

Nanotechnology in the Life Sciences

Mohamed Ahmed Mosa
Synan AbuQamar *Editors*

Applications of Nanotechnology in Plant Disease Management

 Springer

Nanotechnology in the Life Sciences

Series Editor

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Nano and biotechnology are two of the 21st century's most promising technologies. Nanotechnology is demarcated as the design, development, and application of materials and devices whose least functional make up is on a nanometer scale (1 to 100 nm). Meanwhile, biotechnology deals with metabolic and other physiological developments of biological subjects including microorganisms. These microbial processes have opened up new opportunities to explore novel applications, for example, the biosynthesis of metal nanomaterials, with the implication that these two technologies (i.e., thus nanobiotechnology) can play a vital role in developing and executing many valuable tools in the study of life. Nanotechnology is very diverse, ranging from extensions of conventional device physics to completely new approaches based upon molecular self-assembly, from developing new materials with dimensions on the nanoscale, to investigating whether we can directly control matters on/in the atomic scale level. This idea entails its application to diverse fields of science such as plant biology, organic chemistry, agriculture, the food industry, and more.

Nanobiotechnology offers a wide range of uses in medicine, agriculture, and the environment. Many diseases that do not have cures today may be cured by nanotechnology in the future. Use of nanotechnology in medical therapeutics needs adequate evaluation of its risk and safety factors. Scientists who are against the use of nanotechnology also agree that advancement in nanotechnology should continue because this field promises great benefits, but testing should be carried out to ensure its safety in people. It is possible that nanomedicine in the future will play a crucial role in the treatment of human and plant diseases, and also in the enhancement of normal human physiology and plant systems, respectively. If everything proceeds as expected, nanobiotechnology will, one day, become an inevitable part of our everyday life and will help save many lives.

Mohamed Ahmed Mosa • Synan AbuQamar
Editors

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Preface

Over the past decade, **nanotechnology** has been intensively explored in biomedical research, and a paradigm shift has emerged in plant science and agriculture. This shift offers promising opportunities for the development of biodegradable, safe, and engineered nanoparticles that could greatly benefit **climate-smart and sustainable agriculture** in the near future. Among the growing areas of interest in nano-biotechnology is the development of **novel solutions for plant disease control** that are safer, more efficient, and highly targeted, with controlled release capabilities. These advancements have the potential to reduce pesticide usage, mitigate environmental and human health risks, and deliver cost savings to farmers. Despite its promise, the application of nano-biotechnology in plant disease control remains **underexplored**, with relatively few research groups working in this area due to significant knowledge gaps. While encouraging preliminary results have been reported, there is an urgent need to address key research questions on **phytotoxicity, environmental persistence, nontarget organism impacts, biodiversity effects, and human health implications**. Globally, comprehensive comparative data on nanopesticides, nanofertilizers, and nanodelivery systems versus conventional agrochemicals—including their environmental fate—remain scarce. Addressing these challenges calls for a **multidisciplinary approach**, integrating materials science, nanotechnology, biosensing, predictive modeling from large-scale field trials, strategic marketing analysis, and systematic in vitro and in vivo experimentation, underpinned by deep expertise in plant biology and ecosystem dynamics.

This book aims to serve as a **comprehensive resource** for researchers, academics, postgraduate students, and policymakers in the agri-nano-biotechnology field. The primary focus is on understanding how nano-based materials interact with pesticides and fertilizers in field applications, with the goals of improving quality, increasing yield, and minimizing both the quantity of active ingredients used and their associated toxic risks—for crops and ecosystems alike. Organized into **16 chapters across 2 major parts**, the volume offers both detection technologies and application-focused insights: **Part I Detection** focuses on nanodevices and nanomaterials for plant disease detection and management (Chap. 1),

bionanosensors for detecting foodborne microbial pathogens (Chap. 2), nanomaterials in pesticide detection and degradation (Chap. 3), potential applications of nanomaterials in detecting and managing plant-parasitic nematodes (Chap. 4), while **Part II Applications** deals with applications of different types of nanomaterials in plant disease management, which includes recent advances in nanobiotechnology for plant disease management (Chap. 5), future developments of nanoparticle applications for sustainable yields (Chap. 6), nanomaterials as strategies for managing microbial plant diseases (Chap. 7), biogenic metallic nanoparticles as fertilizers and fungicides in sustainable agriculture (Chap. 8), biogenic synthesis of copper-based nanoparticles for plant protection (Chap. 9), phytotoxic effects of nanomaterials and plant defense mechanisms (Chap. 10), antifungal activity of metal-based nanomaterials and plant morpho-physiological responses (Chap. 11), antibacterial activity of metal-based nanomaterials and plant morpho-physiological responses (Chap. 12), nanoparticle toxicity and impacts on plant ecosystems (Chap. 13), silver nanoparticles: synthesis, characterization, and biological applications (Chap. 14), polymeric nanomaterials in plant protection and food packaging (Chap. 15), and applications and risks of nanopesticides in agriculture in (Chap. 16).

The **volume editors** express their sincere gratitude to all contributors for their high-quality, up-to-date chapters and their timely cooperation in addressing editorial queries. We are grateful for the constructive and insightful contributions from researchers worldwide, which have enriched this work. It has been a rewarding experience to read and refine the wealth of knowledge presented in these pages. We also extend our appreciation to the **Springer editorial and production teams** for their critical evaluation, encouragement, and unwavering support, and to our families for their consistent understanding and motivation throughout the preparation of this volume.

We believe this book will deepen the understanding of the interdisciplinary connections between **functional biology** and **nanoscience**, highlighting practical strategies to enhance agricultural applications without environmental risks. Future perspectives and challenges are discussed, with an emphasis on making **green nanotechnology**—including magnetic nanostructures—more technically feasible and economically sustainable.

We have worked diligently to achieve these goals and now invite readers to evaluate how far we have succeeded.

Giza, Egypt
Al Ain, Abu Dhabi, United Arab Emirates

Mohamed Ahmed Mosa
Synan AbuQamar

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About the Editors



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Synan AbuQamar earned his Ph.D. in 2007 from Purdue University, where he also completed postdoctoral training. Since 2019, he has been a Full Professor at the United Arab Emirates University (UAEU). He is a distinguished Plant Molecular Geneticist focusing on the molecular and cellular mechanisms of plant immunity, particularly against necrotrophic pathogens, using tomato and date palm as model crops. He has published over 125 peer-reviewed papers in high-impact journals and is internationally recognized for his contributions to plant molecular biology and pathology. His pioneering work has earned prestigious honors, including the Khalifa Award for Education (2020), the Khalifa International Award for Date Palm and Agricultural Innovation (2023), and the King Hamad Prize in Agricultural Development (2023). Ranked among the world's top 2% of scientists by Stanford University, he also serves on editorial and advisory boards, advancing sustainable agriculture and food security in arid regions.

Part I

Detection

Chapter 1

Nanodevices and Nanomaterials for Plant Disease Detection and Management



Mohamed Ahmed Mosa 

Abstract The continually growing global population—projected to reach 8.6 billion in the year 2030—brings unprecedented stress to sustainable farm productivity, particularly with climate change. To address this, overreliance on conventional agrochemicals, particularly pesticides, has increased immensely in an attempt to ensure global food security. Though these inputs have effectively reduced crop losses, their widespread and often uncontrolled application has caused very negative ecological effects, including pollution of the environment, loss of biodiversity, bioaccumulation, and the emergence of resistant phytopathogens. Rising nanotechnology can offer an improved option in the form of nano-enabled agrochemical products, including nano-fertilizers, nano-pesticides, and nano-sensors. These next-generation inputs exhibit enhanced efficiency, controlled release, target selectivity, and reduced environmental impact through their unique physicochemical characteristics—particularly their high surface area-to-volume ratio and surface reactivity, which can be controlled.

Nanoparticles derived from inorganic, organic, and biomolecular precursors are being engineered for plant defense, insect management, and soil fertilization. Their behavior with complex soil microcosms and microbiota is not yet fully understood, and robust experimental design is required to establish their behavior at the molecular scale. Laboratory studies can provide good predictions of nanoparticle effects on seed germination, plant growth, and antimicrobial activity but need to be supplemented by ecological risk assessments to ensure field use. In addition, in silico modeling and machine learning are gaining traction as strategies for predicting nanoparticle behavior and guiding safe nano-agrochemical design. While repeated commercial application of several nano-formulations has been realized, fears still exist about nanoparticle deposition in crops, microbial perturbation of the soil, and food chain human health hazards. Thus, future innovation and application of nano-

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technology to agriculture must balance innovation and comprehensive environmental safety analyses in the aim to establish a more sustainable and robust system of food production.

Keywords Nanoparticles · Detection · Disease management · Nanodevices · Agriculture

1.1 Introduction

The world's population has increased dramatically over the last several years and is predicted to reach 8.6 billion by 2030. In light of global warming, this presents a significant challenge for researchers in establishing sustainable agriculture output. The use of synthetic agrochemicals has thus multiplied many times over to guarantee an adequate quantity of food for the expanding population. Approximately 4.6 million tonnes of crop protection products are applied worldwide, 90% of which leak into the environment and contaminate agricultural commodities. Among these agricultural agents that have been used for a long time to prevent harm from serious phytopathogens are pesticides. Crop loss decreased by 35–42% as a result of the application of pesticides, which are thought to account for one-third of all agricultural production (Liu et al., 2002; Zhang et al., 2011a, b). Furthermore, if pesticides are not applied, there may be a loss of roughly 32%, 78%, and 54% in grains, fruits, and vegetables, respectively (Cai, 2008). The use of these insecticides is growing daily throughout the world. From 2010 to 2014, Japan had the highest average annual usage (kg/ha) of fungicides and bactericides, followed by Mexico (3.275), France (2.162), the UK (1.332), Germany (1.194), and Brazil (0.814), all of which were higher than the global average (0.32). India (0.058) and the United States (0.229) are the final two nations on the list (Zhang, 2018). Despite having made a substantial contribution to agricultural productivity, these agrochemicals' nondegradable and poisonous nature has caused irreversible harm to the ecosystem as a result of their careless and irresponsible application (Kumaraswamy et al., 2018). Furthermore, according to Dietz and Herth (2011) and Marutescu et al. (2017), the majority of these agrochemicals are not completely absorbed by plants and instead leach into the soil and groundwater before eventually building up in living things as well.

The loss of biodiversity has also been attributed to the global usage of pesticides (Kumar et al., 2013). Furthermore, over the past few decades, the use of pesticides has been linked to a number of diseases in humans and animals as well as decreased intelligence levels and fertility in humans (Zhang, 2018). In addition, the rise in resistance among plant diseases to these agricultural pesticides has emerged as a significant concern (Hahn, 2014; Xing et al., 2017). As a result, there has been a development of new types of agricultural chemical products or an increase in the usage of greater doses of current products. This has led to a jump in costs and has accelerated the emergence of new plant infections. The development of nanotechnology has led to the use of nanotechnological approaches in the production of new

generation agrochemicals. These agrochemicals are not only environmentally friendly and safe at low dosages, but also have major applications in the detecting sector. Next-generation pesticides may consist of nanostructured compounds that selectively and gradually discharge their active components as necessary. Due to the quantum size effect, nanoparticles (NPs) exhibit a wide range of changes in their physical and chemical characteristics, resulting in numerous advantageous uses compared to typical bulk materials, mostly due to their greater surface area to volume ratios.

The remarkable functional characteristics of nanoparticulate substances derived from inorganic, organic (polymeric), and biomolecular sources are being utilized in sustainable agriculture for various nano-enabled products, such as nano-insecticides, nano-pesticides, and nano-fertilizers. In recent times, nanoparticulate materials have emerged as a potential alternative for managing plant pests, including insects, fungi, and weeds. While the fundamental comprehension of nanoscience and technology remains consistent, it necessitates multiple modifications to align with the anticipated nano-enabled characteristics and the specific requirements at hand. For example, the high ratio of surface area to volume in a sample of nanoparticulate material allows for extensive chemical, physical, and biological interactions during its use. Additionally, this ratio also leads to various other characteristics that depend on the environment and the presence of atomic and molecular species, which may be either static or dynamic over the course of time.

Although other properties like disintegration, aggregation, and aggregation are also feasible, surface stabilization of the nanoparticles has always been the most straightforward application of surface reactivity. It is important to mention that any change made to the surface of the nanoparticulate materials results in the development of certain features. While the numerous potential modifications may seem beneficial for creating nanomaterials with desired physical and chemical characteristics, the huge amount of opportunities makes it extremely challenging to manipulate the environment. Therefore, it becomes necessary to guide molecular recognition along particular routes that are more likely to lead to the desired outcome. When nanotechnology is applied in agriculture, dealing with the intricate composition and location-specific features becomes much more challenging if not approached with precautions. Soils are complex combinations of organic, inorganic, and bio-polymeric substances that contain a very diverse and active community of the microbes. In order to investigate the atomic and molecular level biochemical interaction routes between nanoparticulate samples and microbes, it is necessary to meticulously create experimental settings. While it is important to have experimental data and take necessary safeguards, field investigations can provide a different scenario. Given the complex and intertwined nature of soil systems, the experimental observations are meticulously chosen to minimize the impact of other errors. For instance, the impact of various nanoparticles on the processes of seed germination, plant growth, and antibacterial properties is meticulously studied both in controlled laboratory conditions and in living organisms, before expanding the findings to varied practical applications.

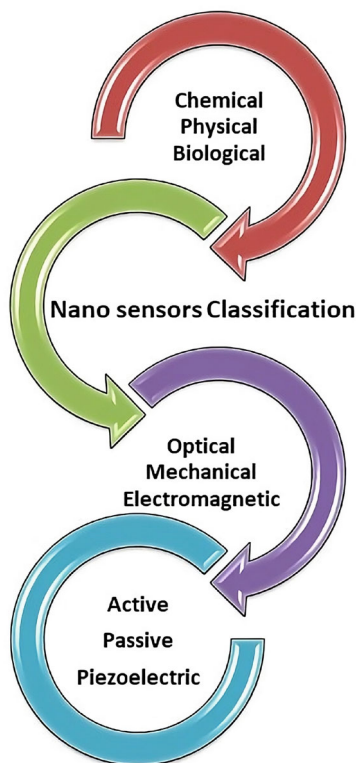
A prominent characteristic of the agro-nanotechnology field is the exclusive utilization of features that have undergone extensive study and have been gathered via experimental research. Investigations make it easier to monitor gradual changes that occur as a result of exposure to varying levels of agricultural chemical products, including nanofertilizers and nanopesticides. Once enough data has been gathered from continuing experimental research, it is possible to use machine learning, artificial intelligence, and other software-based *in silico* approaches to gain a more comprehensive understanding. Significantly, nano-enabled agro-products have already been introduced at commercial level. This is particularly evident in the development of nano-fertilizers with antimicrobial properties for sustainable agriculture, growth stimulants, soil-enhancing agents, and nano-sensors. Additionally, these products are utilised as intelligent and controlled delivery materials to decrease overall costs during application. Nevertheless, the swift utilization of NPs is accompanied with substantial apprehensions over their impact on soil bacteria, their tendency to accumulate in plants, and the potential risk they pose to human health through the food chain. Any discussion in this context would be insufficient without examining the several aspects connected to the safe use of nano-enabled products for environmentally friendly agriculture, with a focus on the ensuing environmental issues.

1.2 Nanoparticle-Based Sensors/Nanosensors

Nano-phytopathology is an advanced discipline that leverages nanoscience to promptly identify, diagnose, and manage plant diseases and their microbial pathogens, hence averting widespread outbreaks in crops. Rapid and effective disease detection is crucial for effective disease control and management in order to minimize crop damage. A research carried out in 2015 by the Associated Chambers of Commerce and Industry of India revealed that the country experienced an annual crop loss of \$500 billion as a result of diseases and pests. (<https://croplife.org/news/keeping-indias-pests-in-line/>). Some conventional techniques for identifying disease include visual detection of morphological structure modifications, serological and electron microscopy, and polymerase chain reaction-based tests of diseased plants (Shang et al., 2011), however these techniques have certain drawbacks. The development of nanobiosensors, which utilize nano and biomolecule assemblies, has been made possible by the emergence of nanomaterials that with unique characteristics including optical capabilities, high electrical conductivity, improved durability against shock, and highly sensitive response mechanisms. These nanobiosensors address the limitations of traditional diagnostic methods (Arora et al., 2020).

In addition, the production of nanomaterials using functionalized metal based nanomaterials as a sensing component offers several beneficial characteristics that are essential for detecting microbial pathogens (Kashyap et al., 2016). A nanobiosensor is a type of biosensor that utilizes nanomaterials, including nanoparticles and nanostructures, to assist farmers in effectively managing plant

Fig. 1.1 Showing different types of nano based sensors



growth. By providing prompt detection of the plants' specific needs, nanobiosensors enable precise control over plant maintenance. Nanobiosensors are crucial in transforming the agricultural industry by creating diagnostic tools and processes. These technologies exhibit great levels of accuracy, increased efficiency, and cost-effectiveness when it comes to agricultural and environmental considerations (Fig. 1.1).

They possess distinctive attributes such as tiny size, high efficiency, compactness, and relatively cost-effectiveness, which render them relatively more significant. Nanobiosensors are utilized in agricultural applications for several purposes, including the detection of pathogens, contaminants, heavy metal ions, microbial load, as well as the quick monitoring of temperature and humidity. Drones play a significant part in decision-making by monitoring crop health, improving water usage efficiency, and providing precise analysis of soil nutrients and pesticide levels for smart agriculture. Nanobiosensors are considered more reliable and sensitive in biosensing approaches compared with traditional sensors due to the distinctive characteristics of nanomaterials, such as strong conductivity, as well as physicochemical, mechanical, and magnetic capabilities (Mathivanan, 2021). The biosensor provides early detection of plant disease with a high level of sensitivity and specificity (Khater et al., 2017).

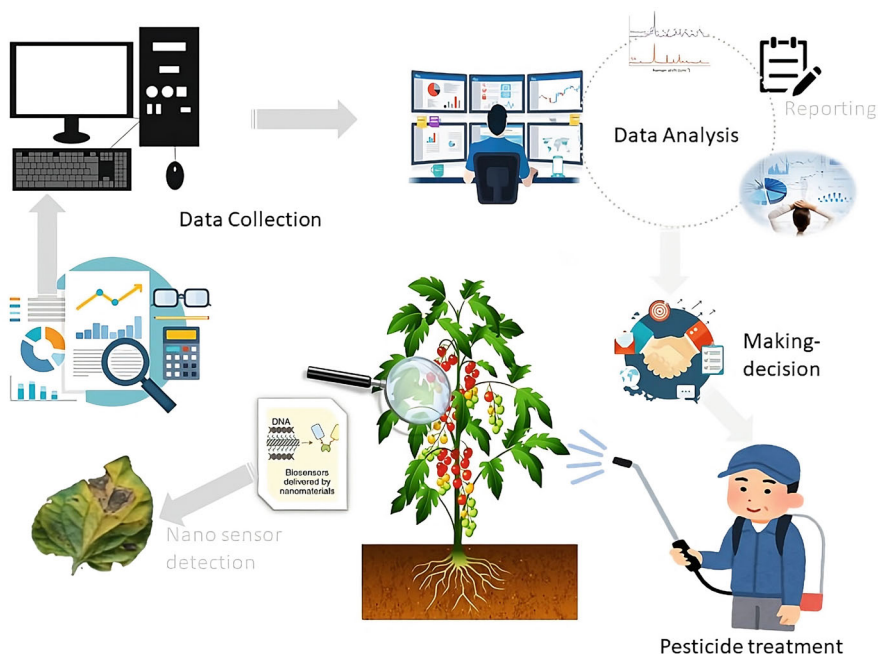


Fig. 1.2 Showing the stages detection and disease management using a nanosensor

A wide range of nanomaterials are employed in the advancement of these biosensors. Silver nanorods are utilized for detecting of a range of plant diseases. The ability for those nanomaterials to detect contaminants and microbial toxins is achieved by the utilization of surface-enhanced Raman spectroscopy, as demonstrated by Li et al. in 2020. Pt nanosensors are employed for the detection of pathogenic bacteria disease in soil and vegetables (Ahmad et al., 2012). Silica based nanomaterials that emit fluorescence and are linked to a secondary antibody can be used to identify the presence of *Xanthomonas axonopodis* pv. *vesicatoria*, a bacterium that causes bacterial spot disease in Solanaceae plants (Yao et al., 2009). In addition, the combination of gold nanoparticles and a particular single-stranded DNA can be used to identify the presence of *Ralstonia solanacearum*, the bacterium that is responsible for causing bacterial wilt disease in potatoes (Khaledian et al., 2017) (Fig. 1.2). A study conducted by Razmi et al. in 2019 found that the genome of tomato yellow leaf curl virus (TYLCV) may be detected in infected plants using localized surface plasmon resonance (LSPR) of gold nanoparticles (AuNPs) (Razmi et al., 2019).

In addition, Lau et al. (2017) presented an overview of an electrochemical biosensor that employs gold nanoparticles for the rapid accurate detection of plant pathogen DNA. This biosensor is designed to be used with disposable screen-printed carbon electrodes. Additionally, they proposed that this sensor had a sensitivity that

was 10,000-fold greater than the standard PCR approach. This nanosensor can detect plant infection induced by *Pseudomonas syringae* even prior to the manifestation of disease symptoms. However, it is possible to monitor plant signalling pathways and metabolism using nano-engineered nanomaterial-based nanosensors. These nanosensors are not destructive, minimally invasive, and allow for real-time study of both biotic and abiotic threats, ultimately leading to enhanced plant wellness. These types of sensors have the capability to monitor chemical outflow with high precision, even at the level of individual molecules. Hence, the monitoring of plant health can be achieved by managing nutrients, controlling diseases, regulating plant hormone levels, and assessing environmental pollutants. Similarly, other types of biosensors utilize nanomaterials for the purpose of detecting chemical pesticides. Bao et al. (2015) constructed a biosensor using a mixture of plant esterase, a substance called chitosan, gold nanoparticles, and graphene nanosheets. This biosensor was designed to detect the presence of organophosphate chemical pesticides in agro-foods, which are known to induce neurotoxicity in individuals. Carbon nanotube sensors were effectively used as stress indicators for recording the generation of reactive oxygen species (ROS) in the tissues of plants in vivo (Ren et al., 2013). The extensive surface area of carbon-based nanoparticles allows for ample opportunities for interactions with the molecules being sensed. Some specific nanoparticles possess this characteristic, rendering them a superior framework for immobilizing desired biomolecules to enhance signal amplification in biosensors used for detecting mycotoxins (Thipe et al., 2018).

Zhang et al. (2019) established a very sensitive method called surface enhanced Raman scattering (SERS) to detect carbaryl chemical pesticides on different fruit surfaces. They achieved this by growing silver nanoparticles directly on non-woven fabric surfaces using polydopamine based compounds inspired by mussels. In addition, the presence of deltamethrin and carbofuran residues in soil can be readily identified using surface-enhanced Raman spectroscopy (SERS) with the help of flexible colloidal gold nanoparticles (AuNPs). For the purpose of distinguishing between carbamate and organophosphate chemical pesticides, a chemiluminescent sensor array has been established, exploiting the triple channel features of luminal-functionalized silver nanoparticles. A preliminary tool has been designed for the label-free colorimetric detection of chlorpyrifos pesticide throughout water and agricultural based products. This tool employs a dispersion of gold based nanomaterials with silk fibroin. The dispersion exhibits a rapid and high-quality response to pesticide sensing, even at a concentration as low as 10 parts per billion (ppb) (Mane et al., 2020). In addition, nanobiotechnology has the capability to facilitate intelligent plant sensors that can connect with and activate electronic devices to enhance plant production, optimize and automate water and agro-chemical application, and enable highly efficient plant chemical characteristics.

Nanomaterials facilitate the transformation of chemical signals sent by plants into digital data, which may be observed by electronic devices from a distance (Giraldo et al., 2019). Kwak et al. (2017) created a plant monitoring system that linked different sensors to a data acquisition system. The system utilized Bluetooth to

transmit data from the data acquisition system to a distant computer monitoring station. The system was seen to carry out many duties, including monitoring and recording of temperature, humidity, soil moisture, and the level of maturity of vegetable and fruit crops. Currently, nanobiosensors are effectively employed for the detection of a diverse array of fertilizers, pesticide, herbicide, pathogens, temperature, humidity, and soil pH (Rai et al., 2012). The development of nanobiosensors and their application methods for detecting and controlling plant diseases, monitoring soil conditions, and other purposes can enhance productivity of crops while minimizing the use of renewable resources (Bhagat et al., 2023). Therefore, the judicious and regulated utilization of nanobiosensors can contribute to the improvement of yields of crops, thereby promoting environmentally friendly agriculture.

1.3 Classification of Nanomaterials

The majority of nanomaterials can be classified into four main categories: carbon-based materials, metal-based materials, dendrimers, and nanocomposite.

1.3.1 Carbon-Based Materials

Carbon-based materials have generated significant commercial attention because of their diverse and innovative characteristics. Their distinctive physical and chemical characteristics, including as electrical conductivity, exceptional strength, structural integrity, electron affinity, and adaptability, contribute to a diverse array of practical applications (Astefanei et al., 2015). According to their characteristics, they were frequently referred to as “wonder materials” in scientific literature (Kah & Hofmann, 2015). These nanomaterials consist primarily of carbon and are typically found in the shape of hollow spheres, ellipsoids, or tubes. Carbon nanomaterials that have a spherical or ellipsoidal shape are commonly known as fullerenes, whilst those with a cylindrical shape are commonly referred to as nanotubes (Khan et al., 2017).

1.3.1.1 Fullerenes

The discovery of fullerenes was made in 1985 by Kroto et al. (1985). The fullerene family typically consists of carbon clusters with less than 20 carbon atoms, which are typically in the sp²-hybrid form and connected by covalent bonds. Typically, carbon atoms are positioned on the surface of the sphere, namely at the points where pentagons and hexagons meet (Zaytseva & Neumann, 2016).

1.3.1.2 Carbon Nanotubes (CNTs)

Carbon nanotubes (CNTs) were first identified by S. Iijima, a Japanese researcher, in 1991. Carbon nanotubes have distinctive cylindrical architectures that can vary in terms of length, diameter, chirality, and the number of layers. Carbon nanotubes (CNTs) can be categorized into two types: single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). Single-walled carbon nanotubes (SWCNTs) typically have a diameter ranging from 1 to 3 nm and a length of a few micrometers. On the other hand, multi-walled carbon nanotubes (MWCNTs) have a diameter ranging from 5 to 40 nm and are approximately 10 μm length (Zaytseva & Neumann, 2016).

1.3.2 Metal-Based Materials

These metal-based, semiconductor-based, or metal-oxide nanomaterials are very interesting due to their mechanical, chemical, optical, electrical, and magnetic characteristics (Stephenson & Hubler, 2015). Nanomaterials may encompass quantum dots, which are densely packed semiconductor crystals consisting of hundreds or thousands of atoms and have dimensions ranging from a few nanometers to a few hundred nm. Modifying the dimensions of quantum dots directly impacts their optical characteristics. Metal-based materials primarily consist of metals and metal oxides, such as aluminum (Al), copper (Cu), gold (Au), silver (Ag), silica (Si), zinc (Zn) nanoparticles, zinc oxide (ZnO), and titanium dioxide (TiO₂) (Trivedi & Hemantaranjan, 2017).

1.3.3 Dendrimers

The discovery of dendrimers dates back to 1978 when Fritz Vögtle made the initial breakthrough. Subsequently, in the early 1980s, Donald Tomalia and his colleagues, Srinivasa-Gopalan and Yarema, also contributed to the advancement of dendrimer research (Srinivasa-Gopalan & Yarema, 2007). The artificial macromolecules mentioned are distinguished by their precise structure, which is a result of having a large number of functional groups and a compact molecular arrangement (Tomalia & Frechet, 2002). These nanomaterials are polymer based materials that are constructed from branched units called dendrons. The dendrons originate from a central atom or set of atoms that serve as the core. The multitude of chains seen on the surface of dendrimers can be customized to carry out precise functions, such as catalyzing processes. The three-dimensional dendrimers possess internal spaces capable of accommodating other molecules, making them potentially valuable for delivering nutrients (Esfand & Tomalia, 2001; Kesharwani et al., 2014).

1.3.4 Composites

Composite based materials involve the integration of nanostructures either with other nanoparticles or with larger substances, such as a combination of mineral oxide nanoparticles and a shell made of a transition metal oxide. The mineral oxide might consist of silica, alumina, or a combination of these substances. For instance, products such as automotive components and packaging components are already incorporating nano-sized clays to improve their mechanical, thermal, barrier, and flame-retardant characteristics. Researchers are currently developing a range of biocomposite nanomaterials (Nair et al., 2010) that have many applications, such as modifying polymeric films in packaging, serving as catalysts, forming metallic semiconductor junctions, and functioning as optical sensors. Nanomaterials have attracted significant interest and significance in scientific and technological domains due to their high activity and specificity. Nanoparticles (NPs) have the potential to positively impact agricultural output as well as safety by interacting with plants. This is due to their unique physiochemical properties, including chemical composition, reactivity, surface area, particle morphology, and tunable pore size (Khodakovskaya et al., 2012; Giraldo et al., 2014). Natural products (NPs) have plant growth-promoting properties, making them highly valuable in the field of agriculture. Due to their beneficial impacts, nanoparticles are commonly referred to as “magic bullets.” These involve nanopesticides, nanofertilizers, and herbicides that specifically target specific cellular organelles in plants. The utilization of nanoparticles as fertilizer presents countless opportunities to enhance crop productivity.

1.4 Nano-pesticides: A New Paradigm in Crop Protection

Chemical Pesticides are used extensively due to their convenient characteristics, efficacy, accessibility, and cost-effectiveness comparison to other control agents. However, the disadvantages linked to pesticides must not be neglected (Mosa & El-Abeid 2023). The indiscriminate use of pesticides has posed a threat to the survival of aquatic species, insect pollinators, and the natural predators of pests. Indeed, they disrupt the natural equilibrium by eliminating pest-control species, resulting in a significant surge in pest populations. In addition, lipophilic based pesticides have a long-lasting presence in the natural ecosystem and accumulate at higher levels as they move up through the food chain. Eventually, they are stored in the fatty tissues of humans and animals, posing a serious threat to human health. Pesticides lack target-specificity due to their susceptibility to leaching, wind dispersal, and spread throughout the ecosystem, resulting in contamination of both soil and groundwater resources. Another disadvantage of pesticides is that they can be damaged before reaching their intended destination due to several environmental factors such as light, temperature, humidity, and the existence of numerous micro-organisms. In their study, Ghormade et al. (2011) found that 90% of applied

Table 1.1 Showing some example of nanoparticles with promising pesticidal activity

Nanoparticles	Host plant	Pesticidal effect	References
Chitosan @CUO	<i>Solanum lycopersicon</i> Mill	<i>Fusarium oxysporum</i> , <i>Fusarium solani</i> , <i>Botrytis cinerea</i>	Mosa & El-Abeid (2023), Ismail et al. (2023), El-Abeid et al. (2024)
Lignin loaded carbon nanoparticles	<i>Zea mays</i>	<i>Fusarium verticillioides</i>	El-Ganainy et al. (2023)
Copper oxide (CuO)	<i>Triticum aestivum</i>	<i>Pythium</i> sp.	Zabrieski et al. (2015)
Copper (Cu)	<i>Lactuca sativa</i> , <i>Vicia sativa</i> , <i>Helianthus annuus</i>	<i>Alternaria alternata</i> , <i>Aspergillus flavus</i> , <i>Fusarium solani</i>	Shah and Belozerovala (2009)
Reduced graphene oxide-CuO NPs (RGO-CuO NPs)	<i>Solanum lycopersicon</i> Mill	<i>Fusarium oxysporum</i>	El-Abeid et al. (2020)
Copper sulfate (CuSO ₄)	<i>Solanum lycopersicon</i> Mill	<i>Alternaria solani</i> , <i>Fusarium oxysporum</i>	Saharan et al. (2015)
Silicon oxide (SiO ₂)	<i>Lactuca sativa</i> , <i>Oryza sativa</i> , <i>Solanum lycopersicon</i> Mill	<i>Sitophilus oryzae</i>	Shah and Belozerovala (2009), Tan et al. (2012), Debnath et al. (2011), Mosa et al. (2022)
Titanium oxide (TiO ₂)	<i>Spinacia oleracea</i>	<i>Rhizoglyphus</i> (<i>Boophilus</i>) <i>microplus</i> (larve and adult)	Zheng et al. (2005), Hong et al. (2005)
Iron oxide (Fe ₂ O ₃)	<i>Arachis hypogaea</i> , <i>Triticum aestivum</i>	<i>Alternaria</i> , <i>Bipolaris</i> , <i>Fusarium</i> sp.	Rui et al. (2016), Khizhnyak et al. (2015)
Silver (Ag)	<i>Tobacco</i> (cv. <i>Xanthi</i> nc) plants, <i>Triticum aestivum</i> , <i>Brassica juncea</i>	<i>Potato Virus Y</i> , <i>Rhizoglyphus</i> (<i>Boophilus</i>) <i>microplus</i> , <i>Hippoboscus maculatus</i>	Cordero et al. (2017); Sharma et al. (2012), Santhoshkumar et al. (2012), Mohamed et al. (2018)

pesticides are ultimately washed away during and after the application process. The excessive use of pesticides in pest management significantly increases costs due to the application of a greater amount of pesticides than necessary. The excessive application of pesticides has adverse effects such as reducing soil biodiversity, nitrogen fixation, and increasing resistance to pests and pathogens (Ghormade et al., 2011).

Nanotechnology has emerged as a contemporary solution to address the limitations associated with conventional methods of preparing and applying pesticides for plant disease management (Table 1.1). Nano-pesticides are formulations containing active chemical components that are in nano-dimensions, which give them completely new qualities. Nano-pesticides possess distinct features compared to their larger counterparts due to their smaller size and higher surface area-to-volume ratio. The use of nano-formulation improves the dispersion and solubility of lipophilic pesticides in water, leading to a rise in the bio-accessibility of pesticides and

the elimination of potential hazards caused by other kinds of organic solvents. The stable aqueous nano-dispersions can be used together with other incompatible pesticides, which undergo chemical reactions in protected solutions. In addition, nano-encapsulation allows for precise regulation of pesticide release, thereby extending the period of the pesticide's effective concentration. Additionally, nano-encapsulation serves to hinder the early breakdown of insecticides. Nano-delivery methods are designed to overcome various biological, ecological, and ecological challenges, enabling precise and targeted release of pesticides. Targeted application of pesticides can greatly improve their effectiveness while reducing the potential for pollution from unused chemicals (Carvalho, 2006). Intelligent versatile delivery systems provide precise and time-sensitive control over the release of pesticides. These systems respond to environmental cues, allowing them to work as preprogrammed and remotely regulated systems.

Therefore, these smart nano-delivery systems guarantee a more efficient use of chemical pesticides by significantly reducing the amount required for effective pest control. This ultimately results to a decrease in the costs associated with pesticide production, waste disposal, and the risk of developing resistance to diseases. Nanocomposites consist of TiO_2 , which is photo-catalytically active, and are deposited on the surface of microcapsules filled with pesticides. This arrangement reduces environmental risks by facilitating the photocatalytic breakdown of leftover pesticide residues (Guan et al., 2011). Finally, nanotechnology offers remedies for pesticide contamination resulting from leaching and surface runoff. Loss control pesticides (LCPs) are created by incorporating specific additives that improve the adhesion properties of nanocarriers as resulting in reduced pesticide losses and less environmental contamination (Jia et al., 2014).

1.5 Mechanism of Action of Nano-pesticides Against Phytopathogens

While there have been many studies conducted on the development of nano-pesticides, the specific mechanism by which these pesticides operate against different plant infections remains unknown. It has been reported functions include loss of membrane integrity and function, impaired uptake of nutrients (repression of genes responsible for transporting iron), depletion of antioxidants, generation of reactive oxygen species (ROS), genotoxicity (causing breaks in double-stranded DNA), and malfunctioning of proteins (such as exchange of metal cationic sites, oxidation of cysteine at iron sites, and destruction of iron-sulfur clusters). These hypothesized systems do not operate individually, but rather work together as a collective defense against several plant diseases. The electrostatic attraction between the positively charged of the nanomaterials and the negative charge of the microbial cell membrane causes the attachment of nanoparticles to pathogen cell membranes (Fraceto et al., 2020).

The active ingredient of nanomaterials in nano-pesticides modifies the morphological characteristics of the membrane. This modification causes membrane depolarization, which in turn changes the permeability of the membrane and affects respiratory activities. Ultimately, this leads to damage to the organelles within the cell, ultimately resulting in cell death. The deterioration of cellular structure can result in the release of metabolites, DNA, proteins, enzymes, and other internal cell components. In addition, nanoparticles (NPs) frequently create indentations in the cell wall of microorganisms, facilitating their access into the periplasmic space and the interior of the cells. The mechanism by which nanomaterials affect the structure of membranes and create pits on cell surfaces has been observed using scanning electron microscopy (SEM) in combination with transmission electron microscopy (TEM) (Masum et al., 2019).

It was shown that the use of biologically produced silver nanoparticles (AgNPs) on *Acidovorax oryzae* strain RS-2 resulted in significant damage to the bacterial cell wall, leaking of nuclear and cytoplasmic contents, and engulfment of structures, ultimately leading to the death of the bacterial cells (Jian et al., 2022). Another study conducted by Ganash et al. (2018) examined the effects of treating *Fusarium graminearum* strain PH-1 with AgNPs generated from green sources. The researchers used TEM and SEM to analyze the treatment's impact, which resulted in the distortion of hyphae and damage of the fungal cell wall, ultimately leading to the death of the fungus. Similarly, the effects of AgNPs on various other phytopathogenic fungi such as *Botrytis cinera*, *Trichosporon asahii*, and *Alternaria alternata* were also observed. Nanoparticles' toxicity is linked to the production of reactive oxygen species (ROS). The generation of free radicals results in the destruction of cell membranes and various biomolecules, such as proteins, causing their denaturation, lipid peroxidation, and DNA damage. The occurrence of DNA damage can involve several types of alterations, such as deletions, duplications, mutations, double-strand breaks, single-strand breaks, and cross-linking of proteins (Zhang et al., 2018). Zhang and his colleagues also documented the interconnection between cell membrane impairment and the generation of reactive oxygen species in the antibacterial mechanisms (Zhang et al., 2018). The transmission electron microscopy (TEM) analysis showed that the presence of AgNPs induces the production of hydroxyl radicals, that in turn damages the cell membrane of *Azotobacter vinelandii* (Kannan et al., 2023).

1.6 Tracking of Nanoparticles in Plant Tissues

Nanoparticles (NPs) should undergo comprehensive characterization to assess their suitability for specific applications and to evaluate their safety in biological systems. Physicochemical characterization is crucial for comprehending the traits, qualities, and functions of a material, including its solubility, dispensability, and stability. The growing attention towards metallic nanoparticles (NPs) has highlighted the necessity of developing techniques to investigate their absorption, changes, and impact on the

ecosystem. Consequently, there is a demand for creating tools that can track and visualize engineered nanoparticles (ENPs) in the soil-plant system, as well as employing advanced microscopic and tracer methods. Micro-X-ray fluorescence and absorption spectroscopy, abbreviated as μ -XRF and μ -XAS, have been employed in certain investigations to examine the movement and buildup of nanoparticles (NPs) within plants. The identification and measurement of nanoparticles (NPs) in plants can be examined through the utilization of single-particle inductively coupled plasma mass spectrometry (sp-ICP-MS), while the arrangement of metals in leaf tissues can be analyzed utilizing X-ray fluorescence microscopy (XFM). X-ray absorption near-edge spectroscopy (XANES) can be used to evaluate metal speciation without causing any harm to the samples. Plant tissues have been analyzed using synchrotron-based X-ray absorption spectroscopy to determine the speciation of metals. This technique can provide insights into the mechanisms governing nutrient bioavailability, mobility, and behavior.

The movement of TiO_2 -NPs in cucumber was analyzed using synchrotron μ -XRF and μ -XANES techniques. In tracer approaches, nanoparticles (NPs) are labeled with appropriate probes to enable analysis using positron emission tomography (PET) or single-photon emission computed tomography (SPECT) for visualizing the internal structures of plant tissues. Labeling metal nanoparticles with radioactive isotopes is a useful technique for accurately and precisely determining the location of nanoparticles in a system. Labeled nanoparticles (NPs) possess comparable surface and chemical composition to unlabeled NPs, thereby accurately representing the behavior of NPs. This is in contrast to other fluorescent labeling procedures that necessitate surface alterations, resulting in the loss of the NPs' true behavior. Intrinsic radiolabeling offers more benefits compared to extrinsic radiolabeling due to the tendency of exogenous radiotracers in extrinsic labeling to detach from the metal core of the NPs. This detachment leads to inaccurate representation of the metal-NP behavior and renders it unsuitable for in vivo investigations. Tracking and imaging can be accomplished by using naturally occurring radioactive isotope-labeled nanoparticles (NPs) and nuclear imaging techniques like as positron emission tomography (PET) or single-photon emission computed tomography (SPECT). These sophisticated tracer methods are anticipated to aid in elucidating processes such as adsorption, translocation, transformation, and assimilation of nanoparticles (NPs) in the soil-plant system, specifically regarding the uptake of NPs by cells and the factors that govern interactions at the nanoscale.

1.7 Ethical and Safety Issues

It is essential to thoroughly assess and deliberate over the ethical and safety concerns associated with the utilization of nanomaterials in agricultural applications. Given the potential existence of nano-products in the food and agriculture sectors, it is commonly recognized that there is a scarcity of trustworthy information regarding the safe utilization of NPs due to the absence of safety assessment regulations. An extensive life cycle assessment (LCA) is necessary to comprehensively evaluate the

environmental effects of nanofertilizers and to develop acceptable fertilizer formulations and optimal dosages for their efficient utilization. Toxicity and risk assessment studies will determine the hazards linked to the dispersion and buildup of Nanoparticles in the food chain. This will allow us to make informed policy choices regarding their wider commercialization and directly impact consumer decisions. Biocompatibility studies are necessary to ensure the successful use of Nanoparticles in commercial applications. The biocompatibility of the NPs is mainly due to the presence of a protein coating that interacts with the cellular components and machinery of the test organism. The metal core in the cell, along with the protein covering, plays a crucial function in metal homeostasis. It not only explains selectivity but also triggers biological reactions when nanoparticles invade the cell. The highly specialized regions of nanoparticles (NPs) interact with cells and control the uptake of NPs and their location within the cells. The clustering of nanoparticles (NPs) can modify some surface characteristics, resulting in varied interactions with cells, altering the surface area that is accessible for protein adsorption, and inducing structural changes in the proteins. This, in turn, can initiate distinct patterns of uptake and localization. Therefore, it is crucial to regulate the process of agglomeration in order to increase the bio-availability, restrict dispersion, while improving safety. The preferentially active absorption of nanoparticles is determined by the net change in amino acid residues, as well as the surface area and protein coating. Therefore, in order to successfully use NPs in commercial applications, it is necessary to conduct nano-toxicological and risk assessment studies.

These studies serve as the foundation for the creation of safe NPs. There is a common perception that the nanoform of a substance is more dangerous than its bulk form counterpart. However, this claim requires extensive examination supported by toxicological evidence. Exposure and risk evaluations rely on investigations pertaining to the environmental destiny of a substance. Several investigations have analyzed nano-agrochemicals in terms of their environmental impacts. However, the findings have been inconclusive, making it difficult to accurately assess the dangers associated with their use. Prioritizing comprehensive risk assessment and conducting biocompatibility studies, specifically focusing on cyto- and phytotoxicity, is crucial for the acceptance of nanoparticles (NPs) and determining their behavior in the soil-plant system. This is essential for ensuring the successful and acceptable use of nanomaterials in agricultural sectors. The development of practical legal frameworks that are acceptable to consumers and the public will be ensured by the combination of regulatory pressure, collaborative efforts across many sectors (such as industry, research, and regulators), and the integration of scientific disciplines with social development and law. To ensure the sustainable development of these technologies and the safe use of nanotechnology, it is necessary to adopt a trans-disciplinary strategy based on the One Health idea. This idea is supported by multiple organizations, such as the World Health Organization (WHO) and the Food and Agriculture Organization (FAO), and its definition is provided by the FAO. The One Health vision serves as a cohesive influence in protecting the health of both humans and animals. Therefore, the use of nanotechnology in agriculture requires a purposeful endeavor to address the challenges posed by the absence or inadequacy of regulations and policies, as mentioned by Camara et al. (2019).

1.8 Challenges and Future Perspectives

Several investigations have demonstrated that nano-based chemical pesticides possess significant promise in the framework of pest control, providing environmental and human health benefits when compared to the utilization of traditional pesticides. By employing nano-formulations that respond to stimuli, it is possible to address the primary challenges associated with traditional pesticides. Certain crucial aspects of stimulus-responsive systems necessitate enhancement prior to their effective commercialization.

One reason for the limited commercialization is that most studies are conducted in colleges and universities, research institutes, or small enterprises established for specific farming objectives. Simultaneously, prominent corporations hold several patents, with the quantity growing each year. Current nano-based products in the agriculture sector face market barriers due to the monopolization of patents by huge corporations, who are strategically holding back their release until they can fully capitalize on the potential of these commercially viable items. Another concern pertains to enhancing the comprehension of the hazards associated with the utilization of nano-based pesticides, that are complicated and inadequately realized. It is previously established that the transportation, bioaccumulation, and breakdown rate of nano-based chemical pesticides vary from those of traditional pesticides. Therefore, additional research is required to gain a deeper understanding of these differences. Insufficient data exists about the impacts of nano-based pesticides on crop health, soil biodiversity, non-target species, and human health. Unfortunately, the progress of nano-based pesticides is hindered by a dearth of efficient approaches to comprehend their mechanisms of action. Assessing the environmental impact of nano-based pesticides is crucial for understanding how these substances interact with land and water organisms. In addition to the aforementioned concerns, it is important to emphasise that economic issues continue to be a significant obstacle to the commercialization of nanopesticides. The upfront expenses associated with the development of nanopesticides are substantial, and their economic benefits can only be realized if they are extensively employed in crop protection, which is not now the situation. Furthermore, the absence of regulation poses a significant drawback to the growth of nanotechnology in the field of agriculture. One additional problem that restricts the commercialization of nanobased pesticides is the exorbitant expense linked to registering a novel active ingredient. The primary obstacles that must be tackled to enhance the commercialization of nano-based herbicides are outlined below:

The objectives include establishing standardized protocols for accurate risk-benefit analysis, conducting further research on the interactions between nanoparticles and plants or pathogens,

- Creating a tracking system to monitor the environmental impact of nanopesticides on food security and human health,
- Advancing international legislation to ensure the safe development and use of stimuli-responsive nanopesticides, and

- Establishing a global network for communication among public and private organisations involved in nanopesticide development.

Prior to the complete commercialization of nano-based products, it is evident that conducting additional comprehensive study would be crucial to tackle these difficulties. It is crucial to foster contact among all potential players, such as universities, research institutes, enterprises, governments, NGOs, and consumers.

1.9 Conclusion

Nanobiotechnology, promoting ecological sustainability, is emerging as a key strategy to support agro-economies and ecosystem services. Plant diagnostic tools must suit diverse farming scales, crop needs, and environmental contexts. Current plant health assessment methods are costly, invasive, and often require centralized lab analysis. Advanced nanotechnology and spectroscopic tools offer promising, precise disease detection and stress symptom identification to improve crop productivity sustainably. However, many remain proof-of-concept and need further validation for real-world application, considering accuracy, specificity, sensitivity, durability, cost, usability, and environmental impact. These sensors can enable precision agriculture by optimizing resource use, benefiting both small- and large-scale farmers. The rapid growth of nanotechnology has spurred collaborations between industry and scientists to develop practical nanopesticides. Studies show nanopesticides outperform traditional forms in disease management, enabling lower doses and reducing non-target effects, potentially compensating for their higher absorption (eco)toxicity concerns. Comprehensive research on nanopesticide bioaccumulation, long-term fate, and environmental risks is essential. Future nanopesticide development should prioritize clear benefits that outweigh potential hazards to ensure safe, effective agricultural use.

References

- Ahmad, F. M., Siddiqui O., Babalola Hui-Fen, Wu (2012) Biofunctionalization of nanoparticle assisted mass spectrometry as biosensors for rapid detection of plant associated bacteria Biosensors and Bioelectronics, 35(1), 235-242. <https://doi.org/10.1016/j.bios.2012.02.055>
- Arora, K. V., Sharma, V., & Sachdeva M. (2020). A multiple pheromone ant colony optimization scheme for energy-efficient wireless sensor networks. *Soft Computing*, 24(1), 543–553. <https://doi.org/10.1007/s00500-019-03933-4>
- Astefanei, A., Núñez, O., & Galceran, M. T. (2015). Characterisation and determination of fullerenes: A critical review. *Analytica Chimica Acta*, 882, 1–21.
- Bao, J. C., Mei, H., Junjie, C., Danqun, L., Mei, H., Xiaogang, Y., Yu, L Lei (2015). Plant Esterase–Chitosan/Gold Nanoparticles–Graphene Nanosheet Composite-Based Biosensor for the Ultrasensitive Detection of Organophosphate Pesticides. *Journal of Agricultural and Food Chemistry*, 63(47), 10319-10326. <https://doi.org/10.1021/acs.jafc.5b03971>

- Bhagat, R., Ingle, A. P., & Chen, H. (2023). Nanosensors and nanobiosensors for sustainable agriculture. In *Nanotechnology in agriculture and agroecosystems* (pp. 93–112). Elsevier.
- Cai, D. W. (2008). Understand the role of chemical pesticides and prevent misuses of pesticides. *Bull Agric Sci Technol*, 1(6), 36–38.
- Camara, M. C., Campos, E. V. R., Monteiro, R. A., do Espirito Santo Pereira, A., de Freitas Proença, P. L., & Fraceto, L. F. (2019). Development of stimuli-responsive nano-based pesticides: Emerging opportunities for agriculture. *Journal of Nanobiotechnology*, 17, 1–19.
- Carvalho, F. P. (2006). Agriculture, pesticides, food security and food safety. *Environmental Science & Policy*, 9(7–8), 685–692.
- Cordero, T., Mohamed, M. A., Lopez-Moya, J. J., & Daròs, J. A. (2017). A recombinant potato virus Y infectious clone tagged with the roseal visual marker (pvy-ros1) facilitates the analysis of viral infectivity and allows the production of large amounts of anthocyanins in plants. *Frontiers in Microbiology*, 8, 611.
- Debnath, N., Das, S., Seth, D., Chandra, R., Bhattacharya, S. C., & Goswami, A. (2011). Entomotoxic effect of silica nanoparticles against *Sitophilus oryzae* (L.). *Journal of Pest Science*, 84, 99–105.
- Dietz, K. J., & Herth, S. (2011). Plant nanotoxicology. *Trends in Plant Science*, 16(11), 582–589.
- El-Abeid, S. E., Mosa, M. A., El-Tabakh, M. A., Saleh, A. M., El-Khateeb, M. A., & Haridy, M. S. (2024). Antifungal activity of copper oxide nanoparticles derived from *Zizyphus spina* leaf extract against fusarium root rot disease in tomato plants. *Journal of Nanobiotechnology*, 22(1), 28.
- El-Abeid, S. E., Ahmed, Y., Daròs, J.-A., Mohamed, M. A. (2020). Reduced graphene oxide nanosheet-decorated copper oxide nanoparticles: A potent antifungal nanocomposite against fusarium root rot and wilt diseases of tomato and pepper plants. *Nanomaterials*, 10(5), 1001. <https://doi.org/10.3390/nano10051001>
- El-Ganainy, S. M., Mosa, M. A., Ismail, A. M., & Khalil, A. E. (2023). Lignin-loaded carbon nanoparticles as a promising control agent against fusarium verticillioides in maize: Physiological and biochemical analyses. *Polymers*, 15(5), 1193.
- Esfand, R., & Tomalia, D. A. (2001). Poly (amidoamine)(PAMAM) dendrimers: From biomimicry to drug delivery and biomedical applications. *Drug Discovery Today*, 6(8), 427–436.
- Fraceto, L. F., Castro, V. L., Grillo, R., Ávila, D. S., Oliveira, H., de Lima, R. (2020). Nanopesticides From Research and Development to Mechanisms of Action and Sustainable Use in Agriculture. Springer International Publishing Cham
- Ganash, M., Abdel Ghany, T. M., & Omar, A. M. (2018). Morphological and biomolecules dynamics of phytopathogenic fungi under stress of silver nanoparticles. *BioNanoScience*, 8, 566–573.
- Ghormade, V., Deshpande, M. V., & Paknikar, K. M. (2011). Perspectives for nano-biotechnology enabled protection and nutrition of plants. *Biotechnology Advances*, 29(6), 792–803.
- Giraldo, J. P., Landry, M. P., Faltermeier, S. M., McNicholas, T. P., Iverson, N. M., Boghossian, A. A., et al. (2014). Plant nanobionics approach to augment photosynthesis and biochemical sensing. *Nature Materials*, 13(4), 400–408.
- Giraldo, J. P., Wu, H., Newkirk, G. M., Kruss, S. (2019). Nanobiotechnology approaches for engineering smart plant sensors. *Nature Nanotechnology*, 14(6), 541–553. <https://doi.org/10.1038/s41565-019-0470-6>
- Guan, H. N., Chi, D. F., Yu, J., & Zhang, S. Y. (2011). Novel photodegradable insecticide W/TiO₂/Avermectin nanocomposites obtained by polyelectrolytes assembly. *Colloids and Surfaces B: Biointerfaces*, 83(1), 148–154.
- Hahn, M. (2014). The rising threat of fungicide resistance in plant pathogenic fungi: Botrytis as a case study. *Journal of Chemical Biology*, 7(4), 133–141.
- Hong, F., Zhou, J., Liu, C., Yang, F., Wu, C., Zheng, L., & Yang, P. (2005). Effect of nano-TiO₂ on photochemical reaction of chloroplasts of spinach. *Biological Trace Element Research*, 105, 269–279.

- Ismail, A. M., Mosa, M. A., & El-Ganainy, S. M. (2023). Chitosan-decorated copper oxide nanocomposite: Investigation of its antifungal activity against tomato gray mold caused by *Botrytis cinerea*. *Polymers*, 15(5), 1099.
- Jia, X., Sheng, W. B., Li, W., Tong, Y. B., Liu, Z. Y., & Zhou, F. (2014). Adhesive polydopamine coated avermectin microcapsules for prolonging foliar pesticide retention. *ACS Applied Materials & Interfaces*, 6(22), 19552–19558.
- Jian, Y., Chen, X., Ahmed, T., Shang, Q., Zhang, S., Ma, Z., & Yin, Y. (2022). Toxicity and action mechanisms of silver nanoparticles against the mycotoxin-producing fungus *Fusarium graminearum*. *Journal of Advanced Research*, 38, 1–12.
- Kah, M., & Hofmann, T. (2015). The challenge: Carbon nanomaterials in the environment: New threats or wonder materials? *Environmental Toxicology & Chemistry*, 34(5), 954.
- Kannan, M., Bojan, N., Swaminathan, J., Zicarelli, G., Hemalatha, D., Zhang, Y., et al. (2023). Nanopesticides in agricultural pest management and their environmental risks: A review. *International Journal of Environmental Science and Technology*, 20(9), 10507–10532.
- Kashyap, P. L., Rai, P., Sharma, S., Chakdar, H., Kumar, S., Pandiyan K., Srivastava A. K., Ranjan, S., Dasgupta, N., Lichtfouse, E. (2016). Nanoscience in food and agriculture 2 nanotechnology for the detection and diagnosis of plant pathogens. Springer International Publishing Cham, pp 253–276
- Kesharwani, P., Jain, K., & Jain, N. K. (2014). Dendrimer as nanocarrier for drug delivery. *Progress in Polymer Science*, 39(2), 268–307.
- Khater, M. A., de la Escosura-Muñiz Arben, M. (2017). Biosensors for plant pathogen detection Biosensors and Bioelectronics 9372-86. <https://doi.org/10.1016/j.bios.2016.09.091>
- Khaledian, S. M., Masoud, N., Shams-bakhsh Saeed, Hoseinzadeh (2017). A sensitive biosensor based on gold nanoparticles to detect *Ralstonia solanacearum* in soil. *Journal of General Plant Pathology*, 83(4), 231-239. <https://doi.org/10.1007/s10327-017-0721-z>
- Khan, M., Li, Tiehu Ting Kai, Zhao Zafar, Ali Abdul, Malik Abbas, Khan Imran, Khan Azeem, Ullah Shasha, Jiao Muhammad, Idrees Chuanyin, Xiong (2017). Effect of multi walled carbon nanotubes and diamond nanoparticles on the structure and properties of carbon foams Diamond and Related Materials, 79119-126. <https://doi.org/10.1016/j.diamond.2017.09.008>
- Khizhnyak, S. V., Shevelyov, D. I., & Samoylova, V. A. (2015). *Influence of biogenic nanoparticles of ferrihydrite on the efficiency of etching wheat seeds* (p. 10). Bulletin of Krasnoyarsk State Agrarian University.
- Khodakovskaya, M. V., De Silva, K., Biris, A. S., Dervishi, E., & Villagarcia, H. (2012). Carbon nanotubes induce growth enhancement of tobacco cells. *ACS Nano*, 6(3), 2128–2135.
- Kroto, H. W., Heath, J. R., O'Brien, S. C., Curl, R. F., & Smalley, R. E. (1985). C60: Buckminsterfullerene. *Nature*, 318(6042), 162–163.
- Kumar, J. N., Bora, A., Kumar, R. N., Amb, M. K., & Khan, S. (2013). Toxicity analysis of pesticides on cyanobacterial species by 16S rDNA molecular characterization. *Proceedings of the International Academy of Ecology and Environmental Sciences*, 3(2), 101.
- Kumaraswamy, R. V., Kumari, S., Choudhary, R. C., Pal, A., Raliya, R., Biswas, P., & Saharan, V. (2018). Engineered chitosan based NMs: Bioactivities, mechanisms and perspectives in plant protection and growth. *International Journal of Biological Macromolecules*, 113, 494–506.
- Kwak, S.-Y., Wong, M. H., Lew, T. T. S., Bisker, G., Lee, M. A., Kaplan, A., Dong, J., Liu, A. T., Koman, V. B., Sinclair, R., Hamann, C., Strano, M. S. (2017). Nanosensor Technology Applied to Living Plant Systems. *Annual Review of Analytical Chemistry*, 10(1), 113–140. <https://doi.org/10.1146/anchem.2017.10.issue-1> <https://doi.org/10.1146/annurev-anchem-061516-045310>
- Lau, H. C., Yu, M., Nguyen, Q. P. (2017). Nanotechnology for oilfield applications: Challenges and impact. *Journal of Petroleum Science and Engineering*, 157, 1160–1169. <https://doi.org/10.1016/j.petrol.2017.07.062>
- Li, H. Y., Zhao, S. N., Zang, S. Q., & Li, J. (2020). Functional metal–organic frameworks as effective sensors of gases and volatile compounds. *Chemical Society Reviews*, 49(17), 6364–6401.

- Liu, C. J., Men, W. J., Liu, Y. J., & Zhang, H. (2002). The pollution of pesticides in soils and its bioremediation. *Systematic Science Comprehensive Studies in Agriculture*, 18(4), 295–297.
- Mane P. C., Shinde, M. D., Varma, S., Chaudhari, B. P., Fatehmulla, A., Shahabuddin, M., Amalnerkar, D. P., Aldhafiri, A. M., Chaudhari, R. D. (2020). Highly sensitive label-free bio-interfacial colorimetric sensor based on silk fibroin-gold nanocomposite for facile detection of chlorpyrifos pesticide. *Scientific Reports*, 10(1). <https://doi.org/10.1038/s41598-020-61130-y>
- Marutescu, L., Popa, M., Saviuc, C., Lazar, V., & Chifiriuc, M. C. (2017). Botanical pesticides with virucidal, bactericidal, and fungicidal activity. In *New pesticides and soil sensors* (pp. 311–335). Academic.
- Masum, M. M. I., Siddiqua, M. M., Ali, K. A., Zhang, Y., Abdallah, Y., Ibrahim, E., et al. (2019). Biogenic synthesis of silver nanoparticles using *Phyllanthus emblica* fruit extract and its inhibitory action against the pathogen *Acidovorax oryzae* strain RS-2 of rice bacterial brown stripe. *Frontiers in Microbiology*, 10, 820.
- Mathivanan, S. (2021). Perspectives of nano-materials and nanobiosensors in food safety and agriculture. In K. Krishnamoorthy (Ed.), *Novel nanomaterials*. IntechOpen. <https://doi.org/10.5772/intechopen.95345>
- Mohamed, M. A., Hussein, H. M., & Ali, A. A. M. (2018). Antifungal activity of different size controlled stable silver nanoparticles biosynthesized by the endophytic fungus *aspergillus terreus*. *Journal of Phytopathology and Pest Management*, 5(2), 88–107.
- Mosa, M. A., & El-Abeid, S. E. (2023). Chitosan-loaded copper oxide nanoparticles: A promising antifungal nanocomposite against fusarium wilt disease of tomato plants. *Sustainability*, 15(19), 14295.
- Mosa, M. A., El-Abeid, S. E., Khalifa, M. M. A., Elsharouny, T. H., El-Baz, S. M., & Ahmed, A. Y. (2022). Smart pH responsive system based on hybrid mesoporous silica nanoparticles for delivery of fungicide to control Fusarium crown and root rot in tomato. *Journal of Plant Pathology*, 104(3), 979–992.
- Nair, R., Varghese, S. H., Nair, B. G., Maekawa, T., Yoshida, Y., & Kumar, D. S. (2010). Nanoparticulate material delivery to plants. *Plant Science*, 179(3), 154–163.
- Rai, V., Acharya, S., & Dey, N. (2012). Implications of nanobiosensors in agriculture. *Journal of Biomaterials and Nanobiotechnology*, 3, 315–324.
- Razmi, A., Golestanipour A., Nikkhah, M., Bagheri, A., Shamsbakhsh, M., Malekzadeh-Shafaroud, S. (2019). Localized surface plasmon resonance biosensing of tomato yellow leaf curl virus. *Journal of Virological Methods*, 267, 1–7. <https://doi.org/10.1016/j.jviromet.2019.02.004>
- Ren, X., Jiaying, Li Xiaoli, Tan Xiangke, Wang (2013) Comparative study of graphene oxide activated carbon and carbon nanotubes as adsorbents for copper decontamination. *Dalton Transactions* 42(15), 5266. <https://doi.org/10.1039/c3dt32969k>
- Rui, M., Ma, C., Hao, Y., Guo, J., Rui, Y., Tang, X., et al. (2016). Iron oxide nanoparticles as a potential iron fertilizer for peanut (*Arachis hypogaea*). *Frontiers in Plant Science*, 7, 815.
- Saharan, V., Sharma, G., Yadav, M., Choudhary, M. K., Sharma, S. S., Pal, A., et al. (2015). Synthesis and in vitro antifungal efficacy of cu–chitosan nanoparticles against pathogenic fungi of tomato. *International Journal of Biological Macromolecules*, 75, 346–353.
- Santhoshkumar, T., Rahuman, A. A., Bagavan, A., Marimuthu, S., Jayaseelan, C., Kirthi, A. V., et al. (2012). Evaluation of stem aqueous extract and synthesized silver nanoparticles using *Cissus quadrangularis* against *Hippobosca maculata* and *Rhipicephalus* (*Boophilus*) *microplus*. *Experimental Parasitology*, 132(2), 156–165.
- Shah, V., & Belozerova, I. (2009). Influence of metal nanoparticles on the soil microbial community and germination of lettuce seeds. *Water, Air, and Soil Pollution*, 197, 143–148.
- Shang, L., & Liu, G. (2011). Sensor and actuator fault detection and isolation for a high performance aircraft engine bleed air temperature control system. *IEEE Transactions on Control Systems Technology*, 19(5), 1260–1268. <https://doi.org/10.1109/TCST.2010.2076353>

- Sharma, P., Bhatt, D., Zaidi, M. G. H., Saradhi, P. P., Khanna, P. K., & Arora, S. (2012). Silver nanoparticle-mediated enhancement in growth and antioxidant status of brassica juncea. *Applied Biochemistry and Biotechnology*, 167, 2225–2233.
- Srinivasa-Gopalan, S., & Yarema, K. J. (2007). *Nanotechnologies for the life sciences: Dendrimers in cancer treatment and diagnosis* (Vol. 7). Wiley.
- Stephenson, C., & Hubler, A. (2015). Stability and conductivity of self assembled wires in a transverse electric field. *Scientific Reports*, 5(1), 15044.
- Tan, W. M., Hou, N., Pang, S., Zhu, X. F., Li, Z. H., Wen, L. X., & Duan, L. S. (2012). Improved biological effects of uniconazole using porous hollow silica nanoparticles as carriers. *Pest Management Science*, 68(3), 437–443.
- Trivedi, A. K., & Hemantaranjan, A. (2017). Special supplement 5. *Advances in Plant Physiology*, 15, 106.
- Thipe, V. C., Keyster, M., Katti, K. V., Abd-El salam, K. A., Prasad, R. (2018). Nanobiotechnology Applications in Plant Protection Sustainable Nanotechnology: Mycotoxin Detection and Protection. *Springer International Publishing Cham*, 323–349.
- Tomalia, D. A., Fréchet, J. M. J. (2002). Discovery of dendrimers and dendritic polymers: A brief historical perspective*. *Abstract Journal of Polymer Science Part A: Polymer Chemistry*, 40(16), 2719–2728. 10.1002/pola.v40:16 10.1002/pola.10301
- Xing, K., Liu, Y., Shen, X., Zhu, X., Li, X., Miao, X., & Qin, S. (2017). Effect of O-chitosan nanoparticles on the development and membrane permeability of verticillium dahliae. *Carbohydrate Polymers*, 165, 334–343.
- Yao, K. S., Li, S. J., Tzeng, K. C., Cheng, T-C., Chang, C-Y., Chiu, C. Y., Hsu, J. J., Lin, Z. P. (2009). Fluorescence silica nanoprobe as a biomarker for rapid detection of plant pathogens. *Advanced Materials Research*, 79–82, 513–516. <https://doi.org/10.4028/www.scientific.net/AMR.79-82>, <https://doi.org/10.4028/www.scientific.net/AMR.79-82.513>
- Zabrieski, Z., Morrell, E., Hortin, J., Dimkpa, C., McLean, J., Britt, D., & Anderson, A. (2015). Pesticidal activity of metal oxide nanoparticles on plant pathogenic isolates of Pythium. *Ecotoxicology*, 24, 1305–1314.
- Zaytseva, O., & Neumann, G. (2016). Carbon nanomaterials: Production, impact on plant development, agricultural and environmental applications. *Chemical and Biological Technologies in Agriculture*, 3, 1–26.
- Zhang, W. (2018). A long-term trend of cancer-induced deaths in European countries. *Network*, 3(1–2), 1–9.
- Zhang, W., Jiang, F., & Ou, J. (2011a). Global pesticide consumption and pollution: With China as a focus. *Proceedings of the International Academy of Ecology and Environmental Sciences*, 1(2), 125.
- Zhang, X., Xiaolei, Zhang Changliang, Luo Zhengqi, Liu Yiyun, Chen Shilian, Dong Changzhong, Jiang Shikuan, Yang Fubing, Wang Xiangheng, Xiao (2019) Volume-Enhanced Raman Scattering Detection of Viruses Abstract Small, 15(11). 10.1002/sml.v15.11, <https://doi.org/10.1002/sml.201805516>
- Zhang, W. J., van der Werf, W., & Pang, Y. (2011b). A simulation model for vegetable-insect pest-insect nucleopolyhedrovirus epidemic system. *Journal of Environmental Entomology*, 33(3), 283–301.
- Zhang, L., Wu, L., Si, Y., & Shu, K. (2018). Size-dependent cytotoxicity of silver nanoparticles to *Azotobacter vinelandii*: Growth inhibition, cell injury, oxidative stress and internalization. *PLoS One*, 13(12), e0209020.
- Zheng, L., Hong, F., Lu, S., & Liu, C. (2005). Effect of nano-TiO₂ on strength of naturally aged seeds and growth of spinach. *Biological Trace Element Research*, 104, 83–91.

Chapter 2

Bionanosensors in the Detection of Foodborne Microbial Pathogens



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Abstract Food safety is of paramount importance especially in this era of extensive use of packaged and processed foods. The reasons for this are manifold—pathogens becoming more resilient and resistant and evolving at higher rates. The conventional ways of detection demands sophisticated instruments, time, trained personnel etc. Hence there is a dire need to devise user-friendly, highly sensitive and low-cost biosensors for foodborne microbial detection be it in fresh unprocessed plant products or processed food items. Nanobiosensors (NBS) owing to their high sensitivity, small size, very high surf to volume ratio which when combined with high accuracy optical imaging offer promising solutions to this global public health concern. The present review gives a glimpse of the latest technologies in the field of NBS in food borne microbial detection which includes graphene nanomaterials, quantum dot nanomaterials, metal nanoparticles and metal organic frameworks, carbon dots etc. The advantages of these NBSs, possible problems which can come up while upscaling the technique and its potential applications are also discussed.

2.1 Introduction

About 600 million cases of food-borne diseases have been reported every single year claiming about 4,20,000 lives (USDA, 2024). Thus, it is high time that we give importance to hygienic, safe and nutritious food. The major causative agents of contaminated food have been *Campylobacter* spp., *Escherichia coli*, and *Salmonella* spp. which leads to fatality in millions of people each year. The coliform bacteria *Escherichia coli* is mostly not dangerous and is a part of our regular gut microbiota.

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However, various strains of *E. coli* are extremely harmful and are classified into six groups: diffusely adherent *E. coli*, enterohemorrhagic *E. coli*, enteroinvasive *E. coli*, enteroaggregative *E. coli*, enterotoxigenic *E. coli* and enteropathogenic *E. coli*. Of these, *E. coli* O157: H7 is considered as the deadliest form of enterohemorrhagic *E. coli* as it has the ability to produce Shiga toxins and cause lethal Hemolytic Uremic Syndrome (Abdelhamied et al., 2023). The detection of such food-borne pathogens was predominantly done using the conventional methods namely culture methods and the faster approaches like the nucleic acid-based assays, immunological assays and biosensors (Weng et al., 2021). Another concerning factor in the public health domain is the increasing prevalence of food allergies amongst individuals. It is more than a necessity to detect food allergens at extremely low concentrations to allow people with allergies to make informed choices. The use of microfluidic systems that comprise of quantum dots and graphene oxide has gained popularity as they are capable of interacting with the allergens specifically to detect food allergens rapidly and at low concentrations (Weng & Neethirajan, 2016). In a nutshell, biosensors are devices that detect infections by biochemical reactions involving biorecognition components such as tissues, isolated enzymes, antibodies, genetic materials, or aptamers. The correlation of electrical, thermal, or optical signals in the presence of pathogen biomarkers is the foundation of biosensors. The use of molecular and nanotechnology makes it possible to identify pathogens at incredibly low pathogen concentrations quickly and with high sensitivity. As a matter of fact, the incorporation of magnetic, silver, iron, and gold nanoparticles (NPs) into biosensors has proven to enhance their detection capabilities (Valenzuela-Amaro et al., 2023). The usage of nanomaterials (NMs) in every industry is rampantly increasing and precisely in food industry, it has revolutionised the formulation of food, packaging strategies, storage of the food products and the analysis of the quality of food (Bashir et al., 2022). The domain that revolves around smart packaging of food comprises two sub-divisions: active packaging and intelligent packaging. Active packaging deals with gas, moisture, temperature, flavour/odour absorbers/controllers while intelligent packaging gives real time information about the freshness of the food using external or internal indicators (Sundramoorthy et al., 2018). The ability of nanobiosensors (NBS) to detect toxins, pathogens and chemicals in the early stages of food packaging and storage makes it highly beneficial in the food industries (Thakur et al., 2022). Toxins produced by *Clostridium* spp. is worth mentioning as they are a primary cause for botulism and the complications that follow. Earlier methods to detect botulinum neurotoxin in food substances involved injecting mice models with the suspected contaminated food sample and waiting for 3 days to observe the symptoms in them. This method of course delayed treatment in infected patients and therefore an alternative method to detect the toxins had to be designed. Forster Resonance Energy Transfer based nanosensor was used to detect botulinum neurotoxin E (BoNT/E) and a probe that had a cleavage site in the quencher that is specific for BoNT/E. In the presence of the toxin the cleavage of the probe occurs that results in fluorescence and can be quantified. On the contrary, in the absence of the toxin the fluorescence is quenched resulting in no peak (Wang et al., 2020a, b). There have also been studies that have revealed the detection of pesticides in food substances using NMs like gold and

silver, nanohybrids, carbon based NMs, which had electrochemical, fluorescent or colorimetric transducers. These nanosensors have the ability to detect pesticides like malathion, paraoxon, and chlorpyrifos as they are the most discussed amongst the class of pesticides that are used on vegetables and fruits today. These studies proved to be highly beneficial in this domain as the sensors were able to detect pesticides at limits of detection (LODs) that were lower than the maximum residue limit set by Codex Alimentarius (Kumar et al., 2023). In this chapter, we will delve into the threats posed by food borne pathogens and their toxins, various types of NBSs that are used to detect pathogens and toxins; emphasising on the application of carbon dots in food industries, different means by which NBSs are synthesised, application in various domains of food industries and their future prospects.

2.2 Threat Posed by Food Borne Pathogens and Their Toxins

Several studies have shown that the incidence and significance of various foodborne infection are influenced by the relationship between pathogenic organisms, humans, food and the environment. These foodborne illnesses can be caused by microbes like bacteria, fungi etc., or the toxins produced by it. The severity and duration of symptoms associated with this disease vary greatly. Foodborne pathogens are extremely dangerous because of their zoonotic properties and ability to produce toxins that cause illness or even death upon exposure (Elbehiry et al., 2023). These foodborne pathogens contaminate the food causing serious diseases. Foodborne pathogens (e.g. viruses, bacteria, fungi) are biological agents that can cause foodborne diseases. Foodborne diseases occurs when a pathogen is ingested with food and later colonises in a human host, or when a toxic pathogen colonises food and produces a toxin that is then consumed by the human host (Bintsis, 2017).

2.2.1 Foodborne Fungi

The most common fungi which are foodborne pathogens are *Aspergillus* spp., *Penicillium* spp., *Fusarium* spp., etc. which are known to produce mycotoxins which are highly toxic to humans and animals. These fungi are also known to cause grain discoloration, chemical and nutritional changes and reduced germination (Su et al., 2022) and are the major causes of foodborne diseases in humans and livestock. Toxin-producing species of the genera *Aspergillus* (*A. carbonarius*, *A. flavus*, *A. ochraceus*, *A. oryzae*, *A. parasiticus*, *A. versicolor*), *Penicillium* (*P. nordicum*, *P. expansum*, *P. viridicatum*, *P. verrucosum*), *Fusarium* (*F. culmorum*, *F. graminearum*, *F. oxysporum*, *F. verticillioides*, *F. proliferatum*) and *Alternaria* (*A. alternata*, *A. solani*, *A. brassicae*, *A. tenuissima*, *A. tomato*) can biosynthesize toxic secondary metabolites—mycotoxins (aflatoxins, ochratoxin A,

sterigmatocystin, patulin, fumonisins, zearalenone, deoxynivalenol, alternariol, alternariol monomethyl ether, tenuazonic acid) (Akello et al., 2024; Navale et al., 2021).

2.2.1.1 Aflatoxin (AFT)

Aspergillus genus includes some species that are the most dangerous filamentous fungal human pathogens. *A. flavus* was the most frequently encountered species from a variety of foods whereas *A. fumigatus* was found to cause more serious diseases. Numerous reports of *A. fumigatus* from cereals like barley, rice and wheat have been made. This fungus was also frequently found in nuts like walnuts, copra, hazelnuts, and peanuts. *A. niger* was found to produce the dangerous mycotoxins ochratoxin A and fumonisin B2 (Paterson & Lima, 2017). All these species of *Aspergillus* spp. have known to be dangerous and to cause various foodborne diseases. Aflatoxins (AFTs) are secondary metabolites produced by fungi such as *Aspergillus parasiticus*, *A. flavus*, *A. parasiticus*, *A. nomius* etc. These mycotoxins are known for contaminating different food substrates and are toxic even at nanomolar (nM) concentrations. The most common food and environmental species of *Aspergillus* worldwide are AFTs, which by themselves are responsible for about 30% of contamination. AFT is the most carcinogenic and toxic of all the major mycotoxins. *Aspergillus* species, especially *A. flavus* and *A. parasiticus*, produce toxic metabolites called aflatoxins, which are extremely dangerous to human and animal health. Major AFTs AFB1, AFB2, AFG1, and AFG2 can contaminate a range of agricultural products and may be harmful to humans and livestock. AFM1 and AFM2 are typically found in the human body after contaminated milk and milk products are consumed. Another by-product of AFB1 that has been linked to toxicity and cancer is AFM1. These can be found on agricultural products like tree nuts, cottonseed, peanuts, and maize (corn) (Navale et al., 2021). Diseases caused by consumption of aflatoxins are primarily known as aflatoxicosis. Aflatoxin-producing fungi frequently contaminate seeds under stress conditions like extended drought, insufficient irrigation, insect damage, and planting seeds in unsuitable locations. Persistent symptoms of fatigue, appetite loss, fatty liver, jaundice, and decreased milk production in dairy cattle are caused by acute aflatoxicosis. The US Food and Drug Administration (USFDA) has established a maximum limit of 0.05 µg/kg for AFM1 in milk (Da Silva et al., 2021).

2.2.1.2 Alfatrem (AT)

AT is a strong tremorgenic toxin (indole-diterpene) that is produced in small amounts by *A. minisclerotigenes* and *A. flavus*. AT causes noxious food decay that develops on a variety of products and is known to cause neurological disorders. AT is hazardous to both human and animal health because it has been linked to stagger syndromes, a group of neurodegenerative illnesses marked by hyperexcitability and muscle tremors (Navale et al., 2021).

2.2.1.3 Trichothecenes

This toxin is produced by the fungus *Fusarium*. A broad variety of foods have been linked to fusaria, with fruit, beans, vegetables, and cereals being the main sources. There is only a single case of the genus being isolated from beverages (*F. oxysporum*, from cacao beans and leaves) and dairy (*F. verticillioides* from cheese). The fungus *F. verticillioides* is a well-known producer of fumonisin mycotoxin (Paterson & Lima, 2017). *Fusarium* genus is capable of producing various mycotoxins, such as trichothecenes, zearalenone, and fumonisins that have the greatest economic impact and should be especially avoided in barley, maize, and wheat. Worldwide, *Fusarium* species are found in cereal grains with high concentrations of mycotoxin, including barley, wheat, maize, and rice. High humidity and high temperature have been positively correlated with increased *Fusarium* infection in plants (Piacentini et al., 2019). Trichothecenes are a broad class of chemically related mycotoxins that are mainly produced by *Fusarium* genus fungi. They lead to a wide range of toxic effects like bleeding, diarrhoea, and emesis. Trichothecenes can also impair host immune responses because they are extremely immunotoxic. The prevalence of livestock diseases around the world has been a bottleneck in recent years, preventing the sustainable growth of animal husbandry. An important risk factor for an animal's susceptibility to infections and illnesses is mycotoxin contamination in feed (Wu et al., 2018). Trichothecenes, by themselves, are not genotoxic; however, they can exacerbate the genotoxicity of other toxins that are either produced by the intestinal microbiota or found in food, such as pesticides. This novel effect may affect a significant portion of the population given the widespread prevalence of both genotoxins and TCT (Garofalo et al., 2023).

2.2.1.4 Zearalenone (ZEN)

ZEN, also referred to as the F-2 toxin, is a non-steroid mycotoxin with estrogenic effects produced by some *Fusarium* species. In addition to improperly stored food and feed, contaminated grains including oats, corn, wheat, sorghum, and rice are the main source of ZEN. Worldwide, acute and chronic toxicity to humans and animals is a serious concern. Furthermore, ZEN can build up in the body and be harmful to reproduction. The toxicological effects of ZEN in females have been documented by *in vivo* studies. These effects include abnormal hormone levels in the female reproductive systems of rodents and livestock, a depression of ovarian follicle maturation, oocyte death in the follicles, a lack of ovulation, decreased fertility, and increased embryo-lethal resorption (Lee et al., 2022).

2.2.1.5 Ochratoxin A(OTA)

OTA is produced mainly by the genus *Penicillium*, many of which are found all over the world and can grow in a variety of settings, including food products, soil, the air,

and indoors (Lindsay et al., 2023). Many toxins of *Penicillium* are carcinogenic and may harm the kidneys and digestive system too. *Penicillium* does not directly cause disease, but its presence on food suggests a possible health risk because of mycotoxins present. Ochratoxin A(OTA) is a mycotoxin which is found to contaminate a wide range of agricultural products, including cereals, fruits, cocoa, and coffee beans. OTA, the most strictly controlled mycotoxin, exhibits mutagenic, teratogenic, and potentially carcinogenic (group IIB carcinogen) properties. It also poses a major risk to human health (Luo et al., 2022). On meat products, *Penicillium nordicum* and *P. verrucosum* have the ability to produce ochratoxin A (OTA). Consequently, measures to stop OTA contamination in meat products that have ripened are needed (Delgado et al., 2019; Schrenk et al., 2020). Many kidney diseases, including chronic renal failure and Balkan endemic nephropathy, are thought to be influenced by OTA (Kosicki et al., 2021).

2.2.1.6 Patulin (PAT)

Patulin is a mycotoxin produced by *Penicillium expansum*, which remains one of the most important postharvest pathogens in fruits, olives etc. It has been demonstrated that tomatoes which are infected by *P. expansum* and contract the Pome fruit blue mould disease show the presence of PAT. This mycotoxin is teratogenic, genotoxic and potentially immunotoxic. (Rodrigues et al., 2022) Numerous foods, including apples, pears, cherries, walnuts, pecans, olives, hazelnuts and acorns, have been linked to *P. expansum* contamination. It is characterised as a significant PAT producer and the main mycotoxin threat exists for apples and apple-derived goods, including cider, juice, purée, and jam (Hamdi et al., 2021).

2.2.1.7 Citrinin (CTN)

Citrus fruits, wheat, and other cereals are known to contain *Penicillium citrinum*, which can cause contamination with the mycotoxin citrinin (Schmidt et al., 2019). Vegetable juices, herbs and spices and spoiled dairy products have all been found to naturally contain CTN). According to reports, CTN has a deleterious impact on both human and animal health by inducing immunotoxicity, reproductive toxicity, cytotoxicity, and genotoxicity in a variety of mammalian systems. (Chen et al., 2022).

2.2.2 Foodborne Bacteria

Animal foods, which include meat, eggs, milk, and their derivatives, are among the many types of food that can become contaminated by foodborne pathogenic bacteria. Foodborne pathogenic bacteria contamination can also result from environmental pollution in the food production, processing, transportation and sales (Li et al., 2023). Food deterioration is known to be caused by dozens of foodborne pathogenic

bacteria, such as *Salmonella*, *Bacillus cereus*, *Escherichia coli*, *Listeria monocytogenes*, *Vibrio parahaemolyticus*, *Pseudomonas aeruginosa*, and *Vibrio parahaemolyticus*. Food safety is now at risk primarily because some of these bacteria have the ability to secrete toxins and cause illnesses in humans (Cheng et al., 2023). Foodborne illnesses are a global issue, particularly those that are brought about by milk and milk products. Being a complete food, milk is a good medium to activate different bacteria, including *Salmonella typhi*, *Staphylococcus aureus*, and *Listeria monocytogenes*. (Bastam et al., 2021). Table 2.1 summarises the information regarding the various types of bacteria that cause foodborne diseases.

2.3 Nanobiosensors to Detect Food Borne Microbial Pathogens and Their Toxins

2.3.1 Graphene NPs

Carbon atoms are stacked in a honeycomb lattice monolayer to form graphene. Between each of these carbons and its three neighbouring carbon atoms, it forms three intralayer sp^2 or sigma (σ) bonds. Between the interlayers in graphene, there are pi (π) bonds, which are responsible for the attachment of functional groups and electrical and thermal conductivities in graphene. They typically have less strength than sigma bonds and are therefore favourable for sensor applications (Pourmadadi et al., 2021). There have been several incidents reported on aflatoxin M1 contamination in milk and milk products and a highly sensitive detection methodology was necessary to prevent fatalities. The hydroxylated metabolite of aflatoxin B1 (AFB1) is aflatoxin M1 (AFM1) and is present in milk and milk products that are obtained from animals that have consumed tainted feed (Omar, 2016). A graphene oxide based aptamer sensor was used to detect and amplify fluorescence signals in samples that contained AFM1. The aptamer in this study was labelled with a fluorophore called carboxyfluorescein. Graphene oxide being a fluorescent quencher has the ability to quench the fluorescence and interfere with the signal and at the same time protects the aptamer from the attack of nucleases. When a contaminated sample is introduced into the mixture, the aptamer cleaves itself from the graphene oxide and binds to the AFM1 owing to the high specificity forming the AFM1-aptamer complex. This allows the aptamer to emit the fluorescence signals that were masked by graphene oxide before interaction with AFM1. The LOD in this study was found to be 0.05 $\mu\text{g/kg}$ and the range was from 0.2 to 10 $\mu\text{g/kg}$ (Guo et al., 2019).

2.3.2 Metal NPs

Some NPs are used as inorganic nanocarriers and are produced from metal oxides like iron, gold and titanium. Like the organic nanocarriers, they too can undergo surface functionalization to increase the surface area. A NBS was designed using antimony tin

Table 2.1 Bacterial species that cause foodborne diseases

Microorganisms	Food item (s) associated	Toxin	Disease	Symptoms
<i>Salmonella</i> spp.	Poultry, eggs, meat, unpasteurized milk, contaminated fruits and vegetables		Salmonellosis	Diarrhoea, fever, abdominal cramps, nausea, vomiting, headache
<i>Escherichia coli</i> (<i>E. coli</i>) O157: H7	Undercooked beef, unpasteurized milk, contaminated produce	Shiga toxin	<i>E. coli</i> infection, Hemolytic Uremic Syndrome (HUS)	Diarrhoea (often bloody), abdominal cramps, vomiting, fever, kidney failure, anaemia, low platelet count
<i>Listeria monocytogenes</i>	Ready-to-eat foods (deli meats, soft cheeses, unpasteurized milk), raw sprouts		Listeriosis	Fever, muscle aches, headache, nausea, vomiting, diarrhoea,
<i>Campylobacter jejuni</i>	Undercooked poultry, unpasteurized milk, contaminated water		Campylobacteriosis	Diarrhoea, abdominal cramps, fever
<i>Staphylococcus aureus</i>	Meat, poultry, eggs, dairy products, baked goods (improper handling)	Staphylococcal enterotoxin	Staphylococcal food poisoning	Nausea, vomiting, diarrhoea, abdominal cramps, onset usually rapid (within hours)
<i>Bacillus cereus</i>	Rice, starchy foods, meat, vegetables (improper handling and storage)	Emetic toxin, diarrheal toxin	<i>Bacillus cereus</i> food poisoning	Vomiting (emetic type), diarrhoea (diarrheal type)
<i>Clostridium botulinum</i>	Improperly canned foods, honey (infants), smoked fish, cured meats	Botulinum toxin	Botulism	Muscle weakness, paralysis, difficulty breathing, blurred vision, can be fatal
<i>Clostridium perfringens</i>	Meat, poultry, gravy (improper cooking and reheating)	Enterotoxin	<i>Clostridium perfringens</i> food poisoning	Diarrhoea, abdominal cramps, nausea, onset usually 8–24 h after consumption

oxide that is coupled with an enzyme to detect cadmium levels in clam meat and mussels. This was a paper based colorimetric assay wherein the ATONP was functionalized using self-assembly monolayers (SAMs) by offering a significant binding site for the enzyme to crosslink on the NP (NP) surface. In this study, 16-phosphonohexadecanoic acid (16-PHA) was used to functionalize the NP which was then followed by combining with Alkaline Phosphatase enzyme (ALP). The paper based nanosensor which was made of Whatman filter paper grade 41 of pore size 25 μm , had 6 thimbles in which sample and reference standards of cadmium (0.1–10 $\mu\text{g/L}$) could be loaded. The paper was further sandwiched between two nylon membrane filter papers of 0.45 μm pore size. When the ALP enzyme acts on the substrate p-nitrophenyl phosphate, it gives a product- p-nitrophenol which is yellow in colour. In the presence of cadmium, the enzyme is not functional as the active site gets blocked and therefore the coloured reaction is drastically reduced with increase in cadmium concentration and was read colorimetrically at 405 nm. The colour developed in the sample thimble was compared with the reference standard to understand the cadmium heavy metal contamination in the meat samples (Swain & Bhand, 2021).

Melamine is a nitrogen rich compound that is a common adulterant in milk samples and therefore various methods are being explored consistently to test the quality of milk during food inspections. Gold NPs were functionalized with aptamers that had high specificity for melamine. On introducing milk samples adulterated with melamine, the aptamers bound to the melamine and induced aggregation of the gold NPs. This aggregation changes the optical properties of the solution which can be read colorimetrically. The colour change is directly proportional to the concentration of the melamine in the solution. The limit of detection of melamine in milk was 14.9 nM and therefore considered to be a highly sensitive and economical assay. The absorbance was read at 640 and 520 nm where the absorption maxima of the dispersed gold NPs is 520 nm and after aggregation is 640 nm (Hu et al., 2018).

Among the easily perishable food substances, fruits are most consumed and if there is a methodology to increase the shelf-life of such food, that would be a remarkable step to reduce food spoilage and wastage. Bananas treated with varying concentrations of silver NPs for 5 min had a longer shelf life when compared to the untreated banana that reached the fully ripened stage within a period of 14 days. Even after 32 days, the bananas treated with 0.01% AgNPs showed a greenish colour whereas the untreated samples had yellow skin with full brown areas indicating decaying period. The AgNPs coated on the pulp prevented bacterial growth and thereby decay (Nayab & Akhtar, 2023). This is an excellent example where metal NMs can be used not just to detect contaminants but to go a step ahead to prevent contamination and thereby reduce food wastage.

2.3.3 Quantum Dots

In a study conducted by Ren et al. Cadmium Telluride (CdTe) Quantum dots (QDs) and Fe_3O_4 magnetic separation were used to detect *Salmonella typhimurium*. This combination was specifically used for their stable fluorescence and high sensitivity.

The Fe_3O_4 magnetic NPs were coated with aptamers specific to *S. typhimurium* and the QDs were conjugated with a single stranded DNA. When incubated together, the aptamer MNPs formed a duplex with the QD-labelled ssDNA. In the presence of the contaminant *S. typhimurium*, the aptamer MNPs have a higher affinity for the pathogen and binds which leads to cleavage and release of the QD-labelled ssDNA into the solution. The fluorescence can be quantified to calculate the concentration of the pathogen in the given food sample. The limit of detection in this method is 1 CFU/mL and is time saving making it a useful tool to detect pathogens in food samples (Ren et al., 2019).

The contamination of food and agricultural products with mycotoxins is turning into a major global issue and of the known mycotoxins, ochratoxins are a class of structurally similar isocoumarin derivative mycotoxins that are mostly made by specific *Aspergillus* and *Penicillium* fungi. Ochratoxins are primarily divided into three categories based on their chemical structures: ochratoxin A (OTA), ochratoxin B (OTB), and ochratoxin C (OTC). Among them OTA is the most prevalent and dangerous. Numerous agricultural goods have been found to contain the toxin, such as cereals, coffee, chocolate, wine, beer, grapes, dairy, and meat products from animals that consumed grains infected with OTA (Wang et al., 2022). A nanobody (Nb)-mediated förster resonance energy transfer (FRET)-based immunosensor employing quantum dots (Nb-FRET immunosensor) was developed by Tang et al. for the ultrasensitive, single-step, competitive detection of OTA in agricultural goods in order to reduce OTA exposure to consumers. The energy transfer in this assay happens between a donor molecule which is the QD labelled OTA and the acceptor which is the nanobody. Nanobody is an antibody that has exceptionally high specificity towards the OTA. The energy absorbed by the donor is transferred to the acceptor when the molecules are in close proximity. When a sample containing OTA is added to this mixture, the OTA competes with the QD labelled OTA to bind to the nanobody. Higher the concentration of the free OTA in the sample, lesser the chances for QD labelled OTA to interact with antibody and therefore there is a dip in the energy transfer that can be quantified which is evident by the changes in fluorescence. The LOD was observed to be 5 pg/mL which indicates that it is a highly sensitive test that was designed and the assay could be completed in 5 min. To summarise, the energy transfer between the donor and acceptor is inversely proportional to the concentration of the analyte (Tang et al., 2020).

2.3.4 Carbondots

Carbondots (CD) are small, nearly spherical carbon NPs, typically smaller than 10 nm in size. These particles possess unique optical and electronic properties due to their quantum confinement effects, making them valuable in an assortment of applications including bio imaging, sensing, optoelectronics and drug delivery. CDs, known for their photoluminescence, high photostability, low toxicity, and ease of

fabrication are considered to be ideal candidates for detecting food borne pathogens, their toxins and to act as active deterrents of said pathogens through their scope in food packaging. This section will delve into the applications of CDs in most of its forms (Manusuriya & Altintas, 2021), *i.e.*, Carbon Quantum Dots (CQDs), Graphene Quantum Dots (GQDs), Carbon Nanodots (CNDs) and Carbon Polymer Dots (CPDs) in food safety. Table 2.2 depicts use of Carbon dots in biosensing for the detection of food borne pathogens.

Table 2.2 Strategies of biosensing by Carbon dots for the detection of food borne pathogens

Sensing strategy	Organism/toxin	Food substance	LOD	Reference
Fluorescence based sensing using CDs made from papaya powder	<i>E. coli</i>	NA	9.5×10^4 cfu/mL	Wang et al. (2016)
Fluorescence based detection using amikacin tagged CDs	<i>E. coli</i>	Fruit juices	552 cfu/mL	Chandra et al. (2016)
Fluorescence based detection using colistin tagged CDs	<i>E. coli</i>	Urine	567 cfu/mL	Chandra et al. (2017)
		Apple juice	640 cfu/mL	
		Tap water	598 cfu/mL	
Fluorescence based CDs derived from <i>L.plantarum</i>	<i>E. coli</i> (biofilms)	NA		Lin et al. (2018)
Impedometry based Au-GQD based electrode loaded with antibodies	<i>Yersinia enterocolitica</i>	Milk	5 cfu/mL	Savas and Altinas (2019)
Electrochemical sensor made of AuNP- GQD composite loaded with AFB1 antibodies	Aflatoxin B1	Maize	0.11 ng/mL	Bhardwaj et al. (2019)
Electrochemical sensors made of GQDs coated with AFB1 antibodies on a MoS ₂ wafer	AFB1	Maize	0.09 ng/dL	Bhardwaj et al. (2020)
Fluorescence based sensors made of aptamer coated MND and DNA coated CDs	<i>Staphylococcus aureus</i>	NA	8 cfu/mL	Cui et al. (2019)
Quenching based sensors made of MNPs bound to CDs and aptamers	<i>Salmonella typhimurium</i>	Lettuce leaves	138 cfu/mL	Guo et al. (2020)
		Vegetable wash	100 cfu/mL	
Electrochemical DNA based probe made of CDs deposited on MoS ₂ wafer	<i>Listeria monocytogenes</i>	NA	67 fM	Martínez-Periñán et al. (2021)
Fluorescence based detection using neutral red CDs coated with DNA	<i>E. coli</i>	NA	12 nM	Martínez-Periñán et al. (2022)

2.3.4.1 Carbon Dots as Fluorescent Probes for Bacterial Imaging

Several works in bio imaging using CDs, exploit its small size and photoluminescence properties to visualise bacteria. These works, although providing cost effective and simple ways to synthesise CDs were extremely non-specific in nature and contributed to the visualisation of several organisms (Deng et al., 2023; Pal et al., 2018; Tsai et al., 2023). A one-step synthesis of Gram negative specific CDs from papaya powder was carried out by Wang et al. who observed its effects on *E. coli*, Hela cell lines etc. The CDs were shown to detect *E. coli* with a limit of detection of 9.5×10^4 cfu/mL with low cytotoxicity (Wang et al., 2016). An Amikacin tagged Fluorescent CD (CD@Amikacin) that specifically targeted gram negative bacteria displayed good linearity with increasing concentrations of *E. coli* and also found similar results when sensing *E. coli* in fruit juices (Chandra et al., 2016). The same authors also reported an ultrasensitive Colistin tagged Fluorescent CD (CD@Colistin) for *E. coli* and Fe^{3+} . They reported good linearity and showed fluorescence in both the blue and red wavelengths. The CD@Colistin were capable of detecting *E. coli* in urine, apple juice and tap water with a limit of detection (LOD) of 567, 640 and 598 cfu/mL respectively (Chandra et al., 2017). Fluorescent CDs have also been used to image and detect bacterial biofilms of several bacteria such as *Pseudomonas aeruginosa*, *E. coli*, *S. aureus* etc. (Lin et al., 2017; Ritenberg et al., 2016). These biofilms are rampant and a recurring problem in food processing environments owing to the complexity, long operation cycles and large scale of food production in these plants (Carrascosa et al., 2021). Moreover, these biofilms contribute to many food borne infections and often form multispecies colonies making early detection and eradication all the more significant. (Carrascosa et al., 2021) CDs were synthesised from *Lactobacillus plantarum* that thwarted the formation of *E. coli* biofilm. The team assessed the effects using a crystal violet assay and noted a significant decrease in biofilm matter with gradual increases in CD concentration and time. They also observed that although the CDs inhibited and decreased biofilm mass, there were no apparent changes to bacterial count or activity (Lin et al., 2018).

2.3.4.2 Carbon Dots as Carriers of Antibodies

CDs can be conferred onto the surfaces of other metals/NPs and coated with specific antibodies to detect microbes and other microbial toxins. The activity of these probes is highly specific in terms of antibodies being used. A novel immunology-based approach was developed for the detection of *Yersinia enterocolitica* from milk and serum samples by creating a Gold-GQD electrode activated with Anti-*Y. enterocolitica* antibodies and immobilised with BSA and EA. The electrode worked based on the nature of GQDs that allows it to reduce H_2O_2 to H_2O and the impedance of the same when the antibody interacts with the appropriate antigen (Savas & Altintas, 2019). The electron transfer in the electrode was tracked using a

Keithly-4200 semiconductor parameter analyser and changes in current was noted with the addition of H_2O_2 as well as the *Y. enterocolitica* samples. The assay was run with both milk as well as serum at bacterial concentrations of $1\text{--}6.8 \times 10^8$ cfu/mL with an LOD of 5 and 30 cfu/mL for milk and serum respectively. The assay also reacted weakly with other species of *Yersinia*, thus, making it extremely specific to *Y. enterocolitica* (Savas & Altintas, 2019). A gold NP (AuNP), GQD composite linked by 2-aminothiophenol was deposited onto an Indium Titanium Oxide glass electrode (ITO). The AuNP-GQD composite was modified with monoclonal antibodies of Aflatoxin B1 (AFB1). The electrochemical signals of the antigen antibody reactions when exposed to spiked maize, measured using EIS and CV yielded a linear graph for AFB1 with an LOD of 0.11 ng/mL (Bhardwaj et al., 2019). The authors also showed that similar strategies can be used to detect other toxins in food stuff; they employed AFB1 coated GQDs on MoS_2 wafers to test spiked maize. They reported better results than the previous studies with an LOD of 0.09 ng/mL (Bhardwaj et al., 2020).

2.3.4.3 Carbon Dot Based Aptameric Probes

Aptamers are SELEX (Systematic evolution of ligands by exponential enrichment) generated chemical antibodies that can recognize and bind to targets with extremely high specificity. These Aptamers can be loaded onto CDs to act as highly sensitive fluorescent probes or designed in ways to measure the activity electrochemically. A 2019 study in the Journal of Analytical chemistry described the synthesis of a FRET based Apta sensor using Aptamer coated magnetic NDs of Fe_3O_4 conjugated with cyclic DNA coated CDs. In their base state the sensor displayed no fluorescence as the Fe_3O_4 ND switched the CD off, while upon contact with *S. aureus* samples the conjugate breaks, owing to the higher specificity of the aptamer to the bacteria, and the CDs start to fluoresce. The fluorescence displayed good linearity for bacterial concentration up to 10^7 cfu/mL and displayed LOD of 8 cfu/mL (Cui et al., 2019). Similarly, Guo and others reported the development of a ferromagnetic NP bound to CDs and an aptamer for the detection of *S. typhimurium* from lettuce leaves. This works on the principle of the inherent fluorescence of the CDs getting dampened by the binding of the aptamer to the bacteria (quenching). They observed good linearity between the fluorescent change value and the concentration of *S. typhimurium* and arrived at an LOD of 100 cfu/mL for vegetable wash water and 138 cfu/mL for lettuce (Guo et al., 2020).

2.3.4.4 Carbon Dots as Carriers of Probe DNA Sequences

A DNA probe to detect *Listeria monocytogenes* and SARS-CoV2 was prepared by depositing Thiolated CDs onto a Molybdenum Sulphide (MoS_2) base and hybridising probe DNA into the base (Martínez-Perinan et al., 2021). The assays were run with complementary and non-complementary DNA and the response was

recorded by Differential pulse voltammetry (DPV). The assays were extremely specific and had an LOD of 67 fM for *Listeria* and 1.01pM for SARS CoV-2. A year later, the research group reported another DNA based Nano-assay although this time using a simpler method of synthesis and fluorescence based detection for *E. coli*. They prepared Neutral Red- CDs using microwaves and coated them with probe DNA. It was found that the fluorescent intensity (530 nm) of the probe increased upon hybridization with complementary *E. coli* DNA and displayed good linearity with increase in concentration of *E. coli* DNA (55–220 nM). The reported LOD for this method was 12 nM and showed great specificity when tested against other bacterial DNA such as that of *S. aureus* (Martínez-Periñán et al., 2022). Moreover, other strategies have been devised such as modifying molecularly imprinted polymers (MIP) with CDs to enhance electrical conductivity (Guo et al., 2017) or forming MIPs on top of synthesised CDs (Xu et al., 2015) for ultra-specific markers for fungal toxins or bacterial detection. Some of the strategies used by carbon dot (CD) based biosensors in detecting food borne pathogens are depicted in Fig. 2.1.

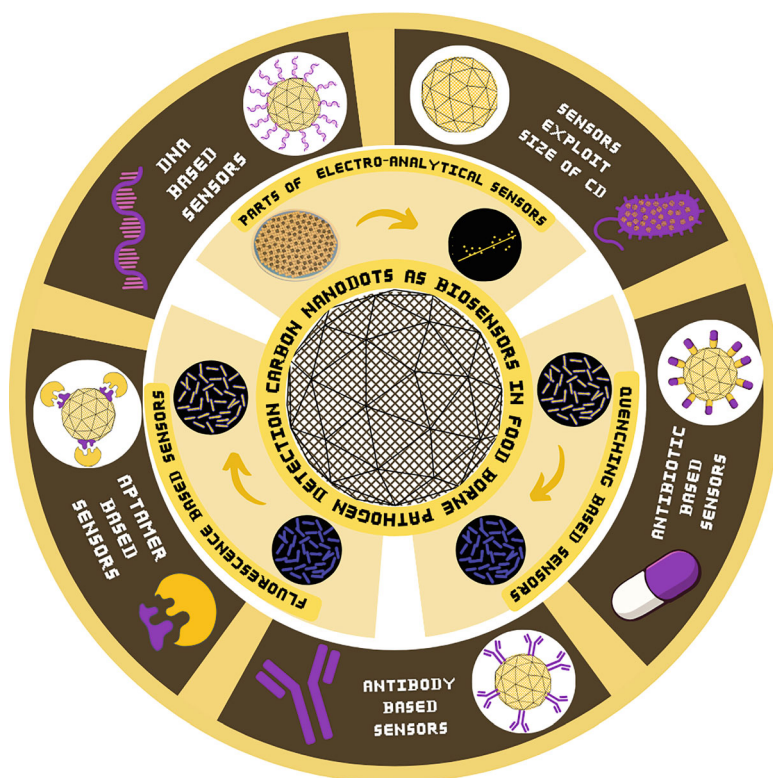


Fig. 2.1 Types of carbon dot (CD) based NBS in detecting food borne pathogens

2.4 Synthesis of NBS

Nanoparticles (NP) are the novel molecules which fall in a size range of 1–100 nm. NPs have various functions and applications in fields like cancer treatments, resonance imaging, tumour detection, biosensor production, etc. There are two approaches for the production of NPs, top down (bulk materials to fine particles) and bottom up (small sub-particles assemble to form NP). The NBS can be produced via a chemical synthesis route or a more sustainable biological synthesis.

2.4.1 Chemical Synthesis

Chemical synthesis of NBS for detecting foodborne microbial pathogens involves creating nanomaterials and functionalizing them with biological recognition elements. There are many types of chemical synthesis approaches depending upon the metal involved in production.

2.4.1.1 Chemical Reduction

Chemical reduction is the most common approach for the production of silver NPs (Ag-NPs). Silver particles (20–80 nm) are chemically synthesised by reducing silver nitrate with glucose in the presence of polyvinyl pyrrolidone (PVP). PVP is used as a dispersant and it (I) protects the formed silver particles from growth and agglomeration, (II) controls the process of reaction and systematic formation of complex compounds. The NaOH:AgNO₃ mole ratio should range between 1.4 and 1.6 for a stable colloid formation whereas for a safe PVP film formation the weight ratio of PVP: AgNO₃ should not go below 1.5. The dispersing ability is dependent on the speed of drops per second as if it goes below 1 drop per second, the particles will agglomerate due to Brownian motion. Ag-NPs have shown effectiveness as an antimicrobial agent against growth of foodborne pathogens such as *Staphylococcus aureus*, *Streptococcus mutans*, *Streptococcus pyogenes*, *E. coli* and *Proteus vulgaris* (Zorraquín-Peña et al., 2020). Silver based bionanosensors are therefore highly effective in detection of such pathogens.

2.4.1.2 Sol-Gel Technique

Sol-gel technique is a type of bottom-up synthesis method known for its high efficiency involving conversion of liquid “sol” to a semi-solid “gel” phase. To prepare a “sol”, metal alkaloids (precursors) such as aqueous tetramethyl-orthosilicate (TMOS) or tetraethyl-orthosilicate (TEOS) go under hydrolysis and polycondensation followed by subsequent drying to obtain NPS in the form

monoliths, glass slides, thin-films or optical fibres (Lin & Brown, 1997). The sol-gel matrix expels out solvent as it ages and the cross-linking increases causing the internal pore size to decrease and trap the species within. This is a concern for sol-gel biosensor application. Thin-films are usually preferred because of its short diffusion path and quick identification of the analyte. Therefore, the process goes as hydrolysis- condensation- calcination (Brinker & Scherer, 1990).

An important application under this technique is Titanium dioxide (TiO_2) NP-based biosensor synthesis. Titanium dioxide (TiO_2) is a type of electrochemical biosensor that converts the electrochemical signals into analytical signal which detects the DNA with a change in output current resistance and conductance (Nadzirah et al., 2020). A Titanium precursor such as titanium tetraisopropoxide, which is very reactive to water, is stabilised by the addition of a complexing agent like acetic acid to undergo hydrolysis/condensation to produce a sol and eventually a gel. The subsequent evaporation and heat treatment produces fine and highly crystalline TiO_2 powders (Marien et al., 2016). As a result of TiO_2 NPs' ability to establish coordination bonds with enzyme carboxyl and amino groups and preserve enzyme activity, these materials have been extensively investigated as glucose sensors or biosensors (Bertel et al., 2021). Titanium dioxide (TiO_2) NPs are synthesised using the sol-gel process and modified with aptamers specific to *Salmonella*, the binding of *Salmonella* to the aptamers alters the photoluminescence properties of TiO_2 , providing a signal indicative of the presence of the pathogen. The application of TiO_2 NPs in the design of PL-based immunosensor suitable for the detection of *Salmonella* (Viter et al., 2017).

2.4.1.3 Reverse Micelles

Reverse micelles (RM), which are nanoscale aqueous droplets present in specific water-in-oil microemulsion compositions (Uskokovic & Drofenik, 2005), are frequently employed in the creation of various kinds of NPs. The molecular basis of an RM microemulsion formation relies on the particular capacity of a surfactant to be adsorbed spontaneously at the free interface between oil and water. A “water-in-oil” microemulsion is formed when water is distributed in a hydrocarbon-based phase. This microemulsion, typically found around the oil apex of a water/oil/surfactant, produces spherical reverse micelles, which minimise surface energy. These micelles act as “nanoreactors,” regulating nucleation and development. The surfactant layer's steric stabilisation prevents NPs from aggregating during later stages of development (Eastoe et al., 2006). Due to the high surface-to-volume ratio and unique physico-chemical characteristics of the NMs, high performance in terms of sensitivity, selectivity, and detection limits have been achieved. As a result, onsite, *in situ*, and online determinations have been made using NBS in a variety of fields, including clinical diagnosis, environmental monitoring, food quality control and processing, pharmaceuticals, and agriculture (Arsene et al., 2021).

The pyrolysis method is a thermal decomposition process that can be used to create NMs for various applications, including the formation of NBS. Pyrolysis

involves heating a precursor material in an inert or reducing atmosphere, leading to its breakdown and the formation of NPs. This bottoms-up synthesis method follows a vapour-phase fabrication which takes a primary precursor (s/l/g) and converts it into the gaseous precursor through evaporation. Gas-phase reaction or supersaturation and gas-solid surface reaction or nucleation turns the gaseous precursor into solid primary particles. The primary particles may be converted to NPs or nanoclusters by following grain growth or agglomeration respectively. Ultrafine NPs with high purity can be produced in one step thanks to high temperature pyrolysis, a significant thermal gradient, and a quick quenching rate caused by the high-velocity spray flame (Mädler et al., 2002). Flame Spray Pyrolysis (FSP) production of Tin Dioxide (SnO₂) NPs have shown promising applications for biosensor production. Because of its system stability, the precursor solutions of Tin (II) 2-ethylhexanoate dissolved in Xylene with different Sn concentrations have produced homogeneous NPs (Li et al., 2020).

2.4.2 Biological Synthesis

Biological synthesis of NBSs involves using biological organisms, biomolecules, or biologically inspired processes to create nanoscale materials that can be integrated into biosensors. This method makes use of biological systems' innate capacity to create NMs with particular characteristics, frequently in ways that are economical and kind to the environment. Because biological synthesis has so many advantages over conventional chemical and physical synthesis methods like eco-friendliness, sustainability, biocompatibility, cost-effectiveness, etc., it is a significant method for creating bio nanosensors.

2.4.2.1 Bacterial Biosynthesis

Several species of bacteria have been discovered to produce NPs in natural conditions as a result of various metabolic processes ongoing in the cell systems. This property may be exploited to obtain naturally produced gold or silver NPs via intercellular or extracellular production mechanisms. Intracellular production of NPs has been observed in bacterial species like *Geobacter ferrireducens* which is a type of Fe (III) reducing species that accumulated precipitated gold (Au) intracellularly in the periplasmic space by the reduction of Au (III) to Au (0) (Kashefi et al., 2001). Other species like *Bacillus subtilis*, Sulphate reducing bacteria (SRB), *Rhodobacter capsulatus* all follow the bioreduction of Au (III) to Au (0) in the cell wall, bacterial envelope and plasma membrane respectively (Beveridge & Murray, 1980; Lengke & Southam, 2006; Feng et al., 2007). Silver NPs (AgNPs) of size 5–15 nm were synthesised by an airborne bacteria *bacillus sp.* which were found deposited in the periplasmic space (Pugazhenthiran et al., 2009). Several other species like *Bacillus cereus* (Sunkar & Nachiyar, 2012), *Pseudomonas stutzeri*

AG259 (Joerger et al., 2000), *Corynebacterium sp.* SH09 (Zhang et al., 2004) etc. produces AgNPs ranging from 5 to 200 nm and with varying sites of intracellular product synthesis.

Extracellular production of NPs has been found in many cases as in the quick biosynthesis of metallic NPs of silver through the reduction of aqueous Ag^+ ions using culture supernatants of *Enterobacter cloacae*, *Escherichia coli*, and *Klebsiella pneumoniae*. AgNPs were formed 5 min after the silver ions came into contact with the cell filtrate, indicating a rapid synthetic process. The bioreduction of silver ions appears to be caused by nitroreductase enzyme (Shahverdi et al., 2007). In another study *Aeromonas sp.* SH10 dried cells quickly reduced $[\text{Ag}(\text{NH}_3)_2]^+$ to Ag^0 in the solution after a small amount of OH^- was added. Stable silver NPs were formed during the bioreduction process, as evidenced by the five broad Bragg reflections on the XRD pattern and the surface plasmon resonance centred at 425 nm on the UV-vis spectra (Fu et al., 2006). Several such reduction mechanisms have been noticed in a variety of bacteria species for the extracellular synthesis of gold, silver, cadmium, zinc, cobalt, etc. NPs.

2.4.2.2 Plant Extract Synthesis

Utilising the natural reducing and stabilising agents found in plant materials, this green and environmentally friendly method of synthesising NP uses extracts from plants. In a recent study, the aqueous plant extracts of Reetha and Shikakai were used to biosynthesize silver NPs. AgNO_3 (1 mM) and (0.625%) ammonia solution were combined with the leaf extract broth. Centrifugation and pellet washing were used to separate the AgNPs that were generated from the broth and supernatant of the leaves. The pellets are hoped to be utilised for additional characterization and as an active substrate for Surface-enhanced Raman spectroscopy (SERS) used to identify members of the genus *Mycobacterium*, particularly *Mycobacterium tuberculosis* (Sur et al., 2018). Another study used the aqueous leaf extracts of *Andrographis paniculata*, *Amaranthus blitum*, and *Amaranthus tricolour* were combined with magnesium precursors and heated at particular temperatures to create MgO NPs. All samples showed a decrease in mixture colour intensity during the heating process, indicating the breakdown of the phytochemicals that functioned as the mixture's stabilising and reducing agents during the creation of MgO NPs (Jeevanandam et al., 2017). It is proved that MgO NPs possess antibacterial properties against *E. coli* and *Staphylococcus aureus* (Makhluf et al., 2005). Such properties have an elaborate application in biomedical fields and plant extract synthesis provides a green and efficient way to stem the potential of bio nanosensor development.

2.4.2.3 Enzyme Mediated Synthesis

Using the catalytic qualities of enzymes, enzyme-mediated NP synthesis is a productive and environmentally benign way to create NPs. Comparing this biogenic

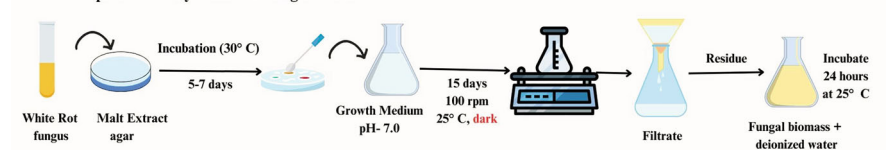
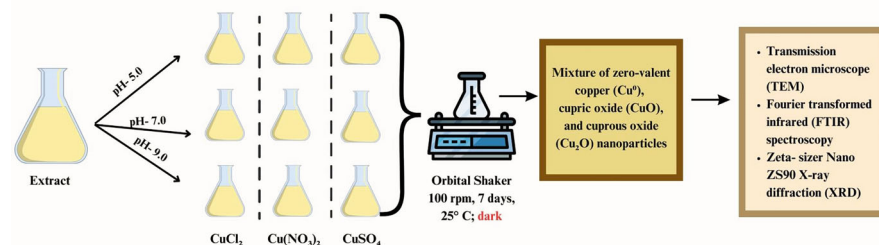
STEP 1: Preparation of mycelium-free fungal-extract**STEP 2: Biosynthesis of Copper/Copper oxide nanoparticles**

Fig. 2.2 Green-synthesis method of production of metal/metal oxide nanoparticles from white rot fungi

approach to traditional chemical and physical approaches reveals some noteworthy advantages like specificity, biocompatibility, cost-effectiveness, control, etc. The biocatalytic manufacture of AgNPs by reducing silver nitrate using immobilised NADH-dependent nitrate reductase as cross-linked enzyme aggregates (CLEA), employed 8-hydroxyquinoline as an electron shuttle and capping agent in addition to NADH as an electron source. The addition of sodium azide, a nitrate reductase inhibitor, hindered the creation of AgNPs, confirming that nitrate reductase CLEAs catalyse the reduction of silver nitrate to produce AgNPs (Talekar et al., 2016). This process possesses potential for a faster and effective large-scale production of AgNPs by simplifying the down streaming process. Fungi harbour many enzymes which can aid in developing NPs. A strategy of green synthesis method of production of metal/metal oxide NPs from white rot fungi is depicted in Fig. 2.2 (Cuevas et al., 2015). Utilising the catalytic qualities of enzymes, enzyme-mediated NP synthesis converts metal ions into NPs in a benign and eco-friendly manner. This procedure takes advantage of innate capacity of enzymes to speed up biological reactions with exceptional efficiency. Table 2.3 lists out few of the successful green synthesis approaches of nanoparticles using various bioagents and their applications.

2.5 Applications

The field of biotechnology has been transformed by NBSs which are advancing rapidly and creatively utilising the properties unique to NMs for detecting various pathogens, especially ones that cause foodborne illnesses. These sensors have shown great promise in enhancing public health and food security through rapid, highly sensitive and specific diagnosis of microbial pathogens in various sectors and industries which include:

Table 2.3 Green synthesis of nanobiosensors using various bioagents and their applications

Nanomaterial	Bioagent	Size (nm)	Shape	Application	Reference
AuNPs	<i>Jatropha integerrima</i>	37.7	Spherical	Biomedical	Suriyakala et al. (2022)
AuNPs	Flavonoid—trisetin	12	Spherical	Antibacterial	Alsamhary et al. (2020)
AuNPs	<i>Capsicum annum</i>	20–30	Spherical	Anti-angiogenic	Patil et al. (2023)
AgNPs	<i>Lysiloma acapulcensis</i>	1.2–62		Antimicrobial	Garibo et al. (2020)
AgNPs	<i>Conocarpus lancifolius</i>	21–173		Anticancer	Oves et al. (2022)
AgNPs	<i>Syzygium cumini</i>	47	Spherical	Anti-inflammatory	Chakravarthy et al. (2022)
Zn nanorods	<i>Leea asiatica</i>	218	Rods	Anticancer	Ali et al. (2021)
Magnetic NPs	<i>Oldenlandia diffusa</i>	–	Monoclinic, rhombohedral	Biomedical	Kong et al. (2023)
FeNPs	<i>Satureja hortensis</i>	9.3–27	Cubic	Antifungal, biomedical	Ahmadi et al. (2021)

2.5.1 Food Processing Industry

In the food processing industry, NBS have become invaluable in food safety monitoring, in terms of sensitivity and specificity and providing tools for detecting contaminants, toxins, and pathogens in food products. Microfluidic Immunosensors offer miniaturisation and portability for pathogen detection in food production lines and thus a microfluidic immunosensor utilising Magnetic nanoparticles (MNPs) was designed to detect *Salmonella typhimurium* with a detection limit as low as 150 CFU/mL (Cai et al., 2019). The food processing sector also utilises gold and silver nanoparticles in various types of biosensors that can easily identify dangerous chemicals or bacteria that may be present in any form of food on the market. An example of this is a gold NP-amplified microcantilever array biosensor which has been developed for detecting ultralow concentrations of pathogens like *Escherichia coli* O157:H7 and *Salmonella* (Zheng et al., 2019a, b). The detection of bacteria like *Salmonella* and *E. coli* has also benefited from the use of PEG-coated gold nanorods (AuNRs) functionalized with sugar. These AuNRs enable specific optical detection and selective photoablation in the food processing industry (Kaushal et al., 2019). In addition, a novel microfluidic biosensor featuring manganese dioxide nanoflowers (MnO₂ NFs) has been designed for swift and accurate identification of *Salmonella Typhimurium* in the food industry. The system utilises the MnO₂ NFs to boost biological signal intensity and combines this with a microfluidic chip and a specialised spiral micromixer for seamless sample processing. The detection process

is completed via a smartphone app and image processing algorithm, allowing for on-site detection with a limit of 44 CFU/mL within 45 min (Xue et al., 2021).

2.5.2 Agricultural Sector

NBS have been shown to significantly enhance the detection of foodborne pathogens in agriculture, offering high sensitivity, specificity, and rapid detection that are essential for crop health and food safety. A DNA-based electrochemical NBS can detect *Phytophthora palmivora*, the causative agent of Black Pod Rot in cacao, using oligonucleotide probes for precise on-site detection (Franco et al., 2019). For oil palm, an MWCNT-based electrochemical sensor detects *Ganoderma boninense*, responsible for basal stem rot, by combining NMR metabolomics with electrochemical sensing to identify infection-associated metabolic changes. This method involves using multi-walled carbon nanotube-chitosan (MWCNT-CTS) and MWCNT-gold NPs to modify the electrode surface, enhancing the electrochemical response and enabling early detection of the pathogen 14 days post-infection, (Isha et al., 2019). Furthermore, an SPR nanosensor with a MIP film and gold NPs provides sensitive, real-time detection of aflatoxin B1 in agricultural products, using the enhanced SPR signal to detect AFB1 at very low concentrations, (Akgönüllü et al., 2020). These NBS enable early intervention and effective management of plant diseases and contaminants, ensuring agricultural productivity and food safety.

2.5.3 Dairy Industry

In the dairy industry, NBS play a crucial role in ensuring the quality and safety of milk and dairy products. One such example is a highly sensitive fluorescent immunosensor using carbon dot-labelled microspheres to detect *Escherichia coli* O157:H7 in milk. The sensor's mechanism relies on *Staphylococcus aureus* cells serving as carriers for the carbon dots within the microspheres, thereby facilitating efficient antibody binding and enhanced detection via immunomagnetic separation. (Zhao et al., 2021). Another development was a DNA-based genosensor for the detection of *Salmonella typhimurium* in milk samples. This sensor uses a bimetallic Fe/Mn MOF and multi-walled carbon nanotubes for high specificity and sensitivity, with a detection limit of 0.07 pM (Sohrabi et al., 2022).

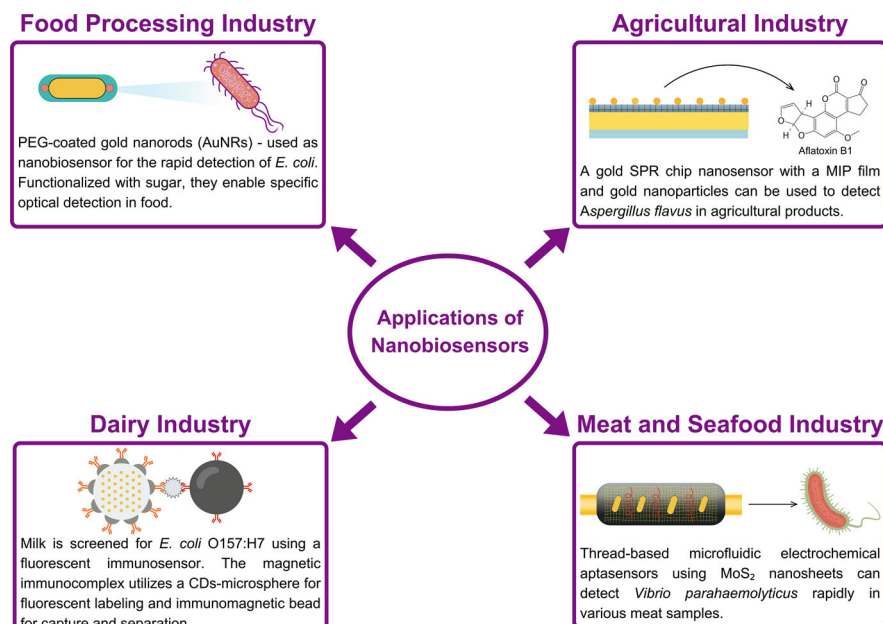


Fig. 2.3 Applications of nanobiosensors in various industries

2.5.4 Meat and Seafood Industry

Much like the other sectors of the food industry, NBS have advanced the detection of foodborne microbial pathogens in the meat, poultry, and seafood industries and thus have enhanced safety protocols by a wide margin. Electrochemical aptasensors using aptamer-coated gold microelectrodes and nickel nanowires can detect *Salmonella typhimurium* with high sensitivity in chicken samples (Wang et al., 2020a, b). Nanoscale piezoelectric immunosensors integrated with magnetic immunoseparation enable rapid and sensitive detection of *Campylobacter jejuni* in poultry products (Wang et al., 2018). In the seafood industry, a versatile thread-based microfluidic electrochemical aptasensor using MoS₂ nanosheets can detect *Vibrio parahaemolyticus* rapidly (Jiang et al., 2021). Another application seen in this industry is a multiplex RPA assay combined with a lateral flow dipstick that has been developed for sensitive detection of multiple pathogens including *Staphylococcus aureus*, *Vibrio parahaemolyticus*, and *Salmonella Enteritidis* in seafood. The test involves binding a tag-specific antibody to the detection line and then cross-linking it with a second tag-specific antibody on colloidal gold NPs (Ma et al., 2020) (Fig. 2.3).

2.6 Advantages

2.6.1 *High Sensitivity and Specificity*

NBSs display remarkable sensitivity and specificity in detecting pathogens. For instance, an immunosensor, consisting of MoS₂ nanosheets attached to a fibre optic SPR platform, efficiently detects *Escherichia coli* by leveraging hydrophobic interactions between the MoS₂ and monoclonal antibodies. This setup exhibits remarkable specificity and sensitivity, with a detection limit of 94 CFU/mL, accompanied by sensitivity of 2.9 nm/1000 CFU/ mL (Kaushik et al., 2019). Traditional techniques, such as culturing, typically require higher concentrations of pathogens to produce a detectable signal, but NBS can detect minute quantities, ensuring early accurate identification of contaminants.

2.6.2 *Rapid Detection*

NBS significantly reduce the time required for pathogen detection, offering results in minutes rather than hours or days. Conventional methods like culture-based techniques often require lengthy incubation periods, sometimes taking several days to confirm the presence of pathogens. In contrast, NBS, such as those incorporating carbon dots for detecting *Escherichia coli* O157:H7, can provide results within 30 min (Zhao et al., 2021). This rapid turnaround is crucial in preventing the spread of foodborne illnesses and allows for quicker responses in food safety management.

2.6.3 *Portability and Ease of Use*

The integration of NBS into portable devices enables on-site testing, making them highly suitable for field applications and settings where resources are limited. For instance, a bionanosensor that employs a capture-antibody-independent lateral flow immunoassay (LFIA) based on Cu_{2-x}Se nanocrystals (Cu_{2-x}Se NCs) for detecting *Escherichia coli* O157:H7 strikes a balance between sensitivity and portability. These nanocrystals serve as “nano-antibodies” for recognizing *E. coli* O157:H7 through electrostatic adsorption and also exhibit good peroxidase-like catalytic activity, allowing for rapid detection within 70 minutes without an external power source. This makes it suitable for swift and effortless deployment in various environments (Yao et al., 2024).

2.6.4 Integration with Digital Technologies

NBS can be combined with digital technologies to provide enhanced functionality and automated analysis. Combining a microfluidic biosensor with a Raspberry Pi allows for automatic analysis of colour images to detect pathogens like *Salmonella typhimurium* (Qi et al., 2021). This integration enables high-throughput screening, data storage, and real-time monitoring, features not found in traditional methods. Digital enhancements provide continuous monitoring, immediate data analysis, and remote reporting, improving the efficiency and effectiveness of food safety protocols.

2.7 Limitations

2.7.1 Cost and Complexity

The cost of NBS is high due to the necessity of advanced NMs and sophisticated manufacturing processes. An optical biosensor that uses porous gold@platinum nanocatalysts, for instance, requires specialised equipment and highly pure materials to achieve high sensitivity. Assembly and design processes also demand skilled personnel and advanced laboratory facilities, limiting widespread adoption in settings where resources are constrained (Zheng et al., 2019a, b). The combination of these factors increases the cost and complexity of NBS technology, making it less accessible for routine use in many food safety monitoring applications.

2.7.2 Interference from Food Matrices

Food samples contain diverse substances that can interfere with the detection capabilities of NBS. Complex matrices can impact the binding efficiency of target pathogens to the sensor's bioreceptors, leading to false positives or negatives. For example, a microfluidic immunosensor designed to detect *Salmonella typhimurium* required additional sample preparation steps, such as filtration or dilution, to minimise interference and avoid non-specific bonding. These extra steps can complicate and lengthen the testing process, detracting from the sensor's convenience and rapid detection capabilities (Cai et al., 2019).

2.7.3 Stability and Reproducibility

Ensuring the long-term stability and reliability of NBS is crucial. Environmental factors such as temperature, humidity, and light exposure can cause NMs and bioreceptors to degrade, impairing their performance over time. For example,

improving the embedding of aptamers and signal molecules in a gold nanobone-enhanced SERS aptasensor for detecting *Escherichia coli* O157:H7 helped maintain stability. However, consistently delivering reliable performance across different batches and ensuring sensors remain effective over extended periods was challenging. Variations in manufacturing processes can introduce batch-to-batch inconsistencies, making reproducible results difficult to achieve (Zhou et al., 2020).

2.7.4 Limited Multiplexing Capabilities

This is a major constraint in the development of NBS. While some sensors can detect multiple pathogens at once, achieving high throughput without compromising sensitivity and specificity is a significant challenge. The integration of multiple bioreceptors on a single platform often leads to cross-reactivity and signal interference. For instance, a multiplex PCR assay designed to quantify *Salmonella* spp., *Escherichia coli*, and *Staphylococcus aureus* simultaneously highlighted the precarious balance required to detect individual pathogens accurately while maintaining high throughput and the potential of decreased sensitivity. Careful and thorough optimization is necessary to balance these factors and ensure accurate detection of multiple pathogens without significant cross-interference (Lopes et al., 2018).

2.8 Future Prospects

As in the case of many other domains, sensing of foodborne pathogens or their toxins in various processed and unprocessed foods have also been benefited by nanotechnology. Last few years saw a number of such technologies being developed for detecting even minute levels of pathogens and the dangerous toxins in food items. Well established norms should be in place when large scale manufacturing of such NBS are carried out as reproducibility of results and limits of detection etc. have to be consistent throughout batches of products. Stability of the sensors is yet another area where consistency has to be brought about. Tackling the concerns of regulatory restrictions and developing cost effective technology for manufacture of such NBS is also the need of the hour. Combination of various NBS would make this approach even better in detecting some of the pathogens and microbial toxins. In future, NBS would definitely have a major role in the accurate and timely detection of food borne pathogens and toxins which in turn will help alleviate the disease burden and mortality contributing to the United Nations Sustainable development goal, SDG3 of Good Health and Well-being.

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References

- Abdelhamied, N., Abdelrahman, F., El-Shibiny, A., & Hassan, R. Y. A. (2023). Bacteriophage-based nano-biosensors for the fast impedimetric determination of pathogens in food samples. *Scientific Reports*, 13(1), 3498. <https://doi.org/10.1038/s41598-023-30520-3>
- Ahmadi, S., Fazilati, M., Nazem, H., & Mousavi, S. M. (2021). Green synthesis of magnetic nanoparticles using *Satureja hortensis* essential oil toward superior antibacterial/fungal and anticancer performance. *BioMed Research International*, 2021, 1–14. <https://doi.org/10.1155/2021/8822645>
- Akello, J., Alamu, E. O., Mwila, C. M., Kachapulula, P. W., Mukanga, M., Njapau, H., Chikoye, D., Ortega-Beltran, A., & Bandyopadhyay, R. (2024). Impact of conservation farming practices on aspergillus population density, peanut aflatoxin level, and exposure risk in Zambia. *Frontiers in Sustainable Food Systems*, 8, 1331188. <https://doi.org/10.3389/fsufs.2024.1331188>
- Akgönüllü, S., Yavuz, H., & Denizli, A. (2020). SPR nanosensor based on molecularly imprinted polymer film with gold nanoparticles for sensitive detection of aflatoxin B1. *Talanta*, 219, 121219. <https://doi.org/10.1016/j.talanta.2020.121219>
- Ali, S., Sudha, K. G., Karunakaran, G., Kowsalya, M., Kolesnikov, E., & Rajeshkumar, M. P. (2021). Green synthesis of stable antioxidant, anticancer and photocatalytic activity of zinc oxide nanorods from *Leea asiatica* leaf. *Journal of Biotechnology*, 329, 65–79. <https://doi.org/10.1016/j.jbiotec.2021.01.022>
- Alsamhary, K., Al-Enazi, N., Alshehri, W. A., & Ameen, F. (2020). Gold nanoparticles synthesised by flavonoid tricetin as a potential antibacterial nanomedicine to treat respiratory infections causing opportunistic bacterial pathogens. *Microbial Pathogenesis*, 139, 103928. <https://doi.org/10.1016/j.micpath.2019.103928>
- Arzene, M., Răut, I., Călin, M., Jecu, M., Doni, M., & Gurban, A. (2021). Versatility of reverse micelles: From biomimetic models to nano (bio)sensor design. *PRO*, 9(2), 345. <https://doi.org/10.3390/pr9020345>
- Bashir, O., Bhat, S. A., Basharat, A., Qamar, M., Qamar, S. A., Bilal, M., & Iqbal, H. M. N. (2022). Nano-engineered materials for sensing food pollutants: Technological advancements and safety issues. *Chemosphere*, 292, 133320. <https://doi.org/10.1016/j.chemosphere.2021.133320>
- Bastam, M. M., Jalili, M., Pakzad, I., Maleki, A., & Ghafourian, S. (2021). Pathogenic bacteria in cheese, raw and pasteurised milk. *Veterinary Medicine and Science*, 7(6), 2445–2449. <https://doi.org/10.1002/vms3.604>
- Bertel, L., Miranda, D. A., & García-Martín, J. M. (2021). Nanostructured titanium dioxide surfaces for electrochemical biosensing. *Sensors*, 21(18), 6167. <https://doi.org/10.3390/s21186167>
- Beveridge, T. J., & Murray, R. G. (1980). Sites of metal deposition in the cell wall of *Bacillus subtilis*. *Journal of Bacteriology*, 141(2), 876–887. <https://doi.org/10.1128/jb.141.2.876-887.1980>
- Bhardwaj, H., Pandey, M. K., Rajesh, & Sumana, G. (2019). Electrochemical Aflatoxin B1 immunosensor based on the use of graphene quantum dots and gold nanoparticles. *Microchimica Acta*, 186, 592. <https://doi.org/10.1007/s00604-019-3701-5>
- Bhardwaj, H., Marquette, C. A., Dutta, P., Rajesh, & Sumana, G. (2020). Integrated graphene quantum dot decorated functionalized nanosheet biosensor for mycotoxin detection. *Analytical and Bioanalytical Chemistry*, 412(25), 7029–7041. <https://doi.org/10.1007/s00216-020-02840-0>
- Bintsis, T. (2017). Foodborne pathogens. *AIMS Microbiology*, 3(3), 529–563. <https://doi.org/10.3934/microbiol.2017.3.529>
- Brinker, C. J., & Scherer, G. W. (1990). *Sol-gel science: The physics and chemistry of sol-gel processing*. Academic.
- Cai, G., Zheng, L., Liao, M., Li, Y., Wang, M., Liu, N., & Lin, J. (2019). A microfluidic immunosensor for visual detection of foodborne bacteria using immunomagnetic separation, enzymatic catalysis and distance indication. *Microchimica Acta*, 186(12), 757. <https://doi.org/10.1007/s00604-019-3883-x>

- Carrascosa, C., Raheem, D., Ramos, F., Saraiva, A., & Raposo, A. (2021). Microbial biofilms in the food industry—A comprehensive review. *International Journal of Environmental Research and Public Health*, 18, 2014. <https://doi.org/10.3390/ijerph18042014>
- Chakravarty, A., Ahmad, I., Singh, P., Sheikh, M. U. D., Aalam, G., Sagadevan, S., & Ikram, S. (2022). Green synthesis of silver nanoparticles using fruits extracts of *Syzygium cumini* and their bioactivity. *Chemical Physics Letters*, 795, 139493. <https://doi.org/10.1016/j.cplett.2022.139493>
- Chandra, S., Chowdhuri, A. R., Mahto, T. K., Samui, A., Sahu, S., & k. (2016). One-step synthesis of amikacin modified fluorescent carbondots for the detection of gram-negative bacteria like *Escherichia coli*. *RSC Advances*, 6, 72471–72478. <https://doi.org/10.1039/C6RA15778E>
- Chandra, S., Mahto, T. K., Chowdhuri, A. R., Das, B., Sahu, S., & k. (2017). One step synthesis of functionalized carbon dots for the ultrasensitive detection of *Escherichia coli* and iron (III). *Sensors and Actuators B: Chemical*, 245, 835–844. <https://doi.org/10.1016/j.snb.2017.02.017>
- Chen, Y., Ye, Y., Wu, H., Wu, Z., Li, P., Fu, Y., Sun, Y., Wang, X., Wang, J., Yang, Z., & Zhou, E. (2022). Citrinin stimulated heterophil extracellular trap formation in chickens. *Molecular Immunology*, 152, 27–34. <https://doi.org/10.1016/j.molimm.2022.09.014>
- Cheng, X., Wang, C. C., Liu, A., Liu, Y., Dong, J., Wang, Z., Wei, W., & Liu, S. (2023). Simultaneous detection of foodborne pathogenic bacteria in milk by fluorescence immunoassay. *Spectrochimica Acta. Part A, Molecular and Biomolecular Spectroscopy*, 285, 121830. <https://doi.org/10.1016/j.saa.2022.121830>
- Cuevas, R., Durán, N., Díez, M. C., Tortella, G. R., & Rubilar, O. (2015). Extracellular biosynthesis of copper and copper oxide nanoparticles by *Stereum hirsutum*, a native white-rot fungus from Chilean forests. *Journal of Nanomaterials*, 2015, 1–7. <https://doi.org/10.1155/2015/789089>
- Cui, F., Sun, J., de Dieu Habimana, J., Yang, X., Ji, J., Zhang, Y., et al. (2019). Ultrasensitive fluorometric angling determination of *Staphylococcus aureus* in vitro and fluorescence imaging in vivo using carbon dots with full-color emission. *Analytical Chemistry*, 91(22), 14681–14690. <https://doi.org/10.1021/acs.analchem.9b03916>
- Da Silva, S. B., Barbosa, J. R., Da Silva Martins, L. H., Moraes, V. S. V., Bichara, C. M. G., Sousa, F. R. S., Da Cruz, E. S., & Lopes, A. S. (2021). Microbial degradation of aflatoxin. In *Environmental and microbial biotechnology* (pp. 1–18). Springer. https://doi.org/10.1007/978-981-16-0518-5_1
- Delgado, J., Núñez, F., Asensio, M. A., & Owens, R. A. (2019). Quantitative proteomic profiling of ochratoxin A repression in *penicillium nordicum* by protective cultures. *International Journal of Food Microbiology*, 305, 108243. <https://doi.org/10.1016/j.ijfoodmicro.2019.108243>
- Deng, Y., Shen, C., Zhao, W., Zheng, G., Jiao, F., Lou, Q., et al. (2023). Biosynthesis of the narrowband deep-red emissive carbon nanodots from eggshells. *ACS Sustainable Chemistry & Engineering*, 11, 6535–6544. <https://doi.org/10.1021/acssuschemeng.2c06892>
- Eastoe, J., Hollamby, M. J., & Hudson, L. (2006). Recent advances in nanoparticle synthesis with reversed micelles. *Advances in Colloid and Interface Science*, 128–130, 5–15. <https://doi.org/10.1016/j.cis.2006.11.009>
- Elbehiry, A., Abalkhail, A., Marzouk, E., Elmanssury, A. E., Almuzaini, A. M., Alfheaid, H., Alshahrani, M. T., Huraysh, N., Ibrahim, M., Alzaben, F., Alanazi, F., Alzaben, M., Anagreyyah, S. A., Bayameen, A. M., Draz, A., & Abu-Okail, A. (2023). An overview of the public health challenges in diagnosing and controlling human foodborne pathogens. *Vaccine*, 11(4), 725. <https://doi.org/10.3390/vaccines11040725>
- Feng, Y., Yu, Y., Wang, Y., & Lin, X. (2007). Biosorption and bioreduction of trivalent Auro by photosynthetic bacteria *Rhodobacter capsulatus*. *Current Microbiology*, 55(5), 402–408. <https://doi.org/10.1007/s00284-007-9007-6>
- Franco, A. J. D., Merca, F. E., Rodriguez, M. S., Balidion, J. F., Migo, V. P., Amalin, D. M., Alolicja, E. C., & Fernando, L. M. (2019). DNA-based electrochemical nanobiosensor for the detection of *Phytophthora palmivora* (Butler) Butler, causing black pod rot in cacao (*Theobroma cacao* L.) pods. *Physiological and Molecular Plant Pathology*, 107, 14–20. <https://doi.org/10.1016/j.pmp.2019.04.004>

- Fu, M., Li, Q., Sun, D., Lu, Y., He, N., Deng, X., Wang, H., & Huang, J. (2006). Rapid preparation process of silver nanoparticles by bioreduction and their characterizations. *Chinese Journal of Chemical Engineering*, 14(1), 114–117. [https://doi.org/10.1016/s1004-9541\(06\)60046-3](https://doi.org/10.1016/s1004-9541(06)60046-3)
- Garibo, D., Borbón-Núñez, H. A., De León, J. N. D., Mendoza, E. G., Estrada, I., Toledano-Magaña, Y., Tiznado, H., Ovalle-Marroquin, M., Soto-Ramos, A. G., Blanco, A., Rodríguez, J. A., Romo, O. A., Chávez-Almazán, L. A., & Susarrey-Arce, A. (2020). Green synthesis of silver nanoparticles using *Lysiloma acapulcensis* exhibit high-antimicrobial activity. *Scientific Reports*, 10(1), 12805. <https://doi.org/10.1038/s41598-020-69606-7>
- Garofalo, M., Payros, D., Penary, M., Oswald, E., Nougayrède, J., & Oswald, I. (2023). A novel toxic effect of foodborne trichothecenes: The exacerbation of genotoxicity. *Environmental Pollution*, 317, 120625. <https://doi.org/10.1016/j.envpol.2022.120625>
- Guo, W., Pi, F., Zhang, H., Sun, J., Zhang, Y., & Sun, X. (2017). A novel molecularly imprinted electrochemical sensor modified with carbon dots, chitosan, gold nanoparticles for the determination of Patulin. *Biosensors & Bioelectronics*, 98, 299–304. <https://doi.org/10.1016/j.bios.2017.06.036>
- Guo, X., Wen, F., Qiao, Q., Zheng, N., Saive, M., Fauconnier, M.-L., & Wang, J. (2019). A novel graphene oxide-based Aptasensor for amplified fluorescent detection of aflatoxin M1 in milk powder. *Sensors (Basel, Switzerland)*, 19(18), 3840. <https://doi.org/10.3390/s19183840>
- Guo, Z., Huang, X., Li, Z., Shi, J., Zhai, X., Hu, X., Liang, N., & Zou, X. (2020). Rapid and highly sensitive detection of salmonella typhimurium in lettuce by using magnetic fluorescent nanoparticles. *Analytical Methods*, 12(48), 5861–5868. <https://doi.org/10.1039/D0AY01744B>
- Hamdi, M., Bejaoui, H., Sá-Morais, J., & Rodrigues, P. (2021). Ecophysiology of penicillium expansum and patulin production in synthetic and olive-based media. *Fungal Biology*, 125(2), 95–102. <https://doi.org/10.1016/j.funbio.2019.08.005>
- Hu, X., Chang, K., Wang, S., Sun, X., Hu, J., & Jiang, M. (2018). Aptamer-functionalized AuNPs for the high-sensitivity colorimetric detection of melamine in milk samples. *PLoS One*, 13(8), e0201626. <https://doi.org/10.1371/journal.pone.0201626>
- Isha, A., Akanbi, F. S., Yusof, N. A., Osman, R., Mui-Yun, W., & Abdullah, S. N. A. (2019). An NMR metabolomics approach and detection of *Ganoderma boninense*-infected oil palm leaves using MWCNT-based electrochemical sensor. *Journal of Nanomaterials*, 2019, 1–12. <https://doi.org/10.1155/2019/4729706>
- Jeevanandam, J., Chan, Y. S., & Danquah, M. K. (2017). Biosynthesis and characterization of MgO nanoparticles from plant extracts via induced molecular nucleation. *New Journal of Chemistry*, 41(7), 2800–2814. <https://doi.org/10.1039/c6nj03176e>
- Jiang, H., Sun, Z., Guo, Q., & Weng, X. (2021). Microfluidic thread-based electrochemical aptasensor for rapid detection of *Vibrio parahaemolyticus*. *Biosensors and Bioelectronics*, 182, 113191. <https://doi.org/10.1016/j.bios.2021.113191>
- Joerger, R., Klaus, T., & Granqvist, C. G. (2000). Biologically produced Silver–Carbon composite materials for optically functional thin-film coatings. *Wiley Advanced*, 12, 407–409. [https://doi.org/10.1002/\(SICI\)1521-4095\(200003\)12:6<407::AID-ADMA407>3.0.CO;2-O](https://doi.org/10.1002/(SICI)1521-4095(200003)12:6<407::AID-ADMA407>3.0.CO;2-O)
- Kashefi, K., Tor, J. M., Nevin, K. P., & Lovley, D. R. (2001). Reductive precipitation of gold by dissimilatory FE(III)-reducing bacteria and archaea. *Applied and Environmental Microbiology*, 67(7), 3275–3279. <https://doi.org/10.1128/aem.67.7.3275-3279.2001>
- Kaushal, S., Priyadarshi, N., Pinnaka, A. K., Soni, S., Deep, A., & Singhal, N. K. (2019). Glycoconjugates coated gold nanorods based novel biosensor for optical detection and photothermal ablation of food borne bacteria. *Sensors and Actuators B: Chemical*, 289, 207–215. <https://doi.org/10.1016/j.snb.2019.03.096>
- Kaushik, S., Tiwari, U. K., Pal, S. S., & Sinha, R. K. (2019). Rapid detection of *Escherichia coli* using fiber optic surface plasmon resonance immunosensor based on biofunctionalized molybdenum disulfide (MoS₂) nanosheets. *Biosensors and Bioelectronics*, 126, 501–509. <https://doi.org/10.1016/j.bios.2018.11.006>

- Kong, Y., Velu, P., Vijayalakshmi, A., & Yuan, C. (2023). Green synthesis of magnetic nanoparticles from *Oldenlandia diffusa*: Characterization and therapeutic activities. *Journal of Biomedical Nanotechnology*, 19(8), 1337–1345. <https://doi.org/10.1166/jbn.2023.3660>
- Kosicki, R., Buharowska-Donten, J., & Twarużek, M. (2021). Ochratoxin A levels in serum of polish dialysis patients with chronic renal failure. *Toxicon*, 200, 183–188. <https://doi.org/10.1016/j.toxicon.2021.08.002>
- Kumar, A., Nirmal, P., Kumar, M., Jose, A., Tomer, V., Oz, E., Proestos, C., Zeng, M., Elobeid, T., Sneha, K., & Oz, F. (2023). Major phytochemicals: Recent advances in health benefits and extraction method. *Molecules*, 28(2), 887. <https://doi.org/10.3390/molecules28020887>
- Lee, R., Kim, D., Lee, W., & Park, H. (2022). Zearalenone induces apoptosis and autophagy in a spermatogonia cell line. *Toxins*, 14(2), 148. <https://doi.org/10.3390/toxins14020148>
- Lengke, M., & Southam, G. (2006). Bioaccumulation of gold by sulfate-reducing bacteria cultured in the presence of gold(I)-thiosulfate complex. *Geochimica et Cosmochimica Acta*, 70(14), 3646–3661. <https://doi.org/10.1016/j.gca.2006.04.018>
- Li, H., Pokhrel, S., Schowalter, M., Rosenauer, A., Kiefer, J., & Mädler, L. (2020). The gas-phase formation of tin dioxide nanoparticles in single droplet combustion and flame spray pyrolysis. *Combustion and Flame*, 215, 389–400. <https://doi.org/10.1016/j.combustflame.2020.02.004>
- Li, Y., Kou, J., Han, X., Qiao, J., Zhang, W., Man, S., & Ma, L. (2023). Argonaute-triggered visual and rebuilding-free foodborne pathogenic bacteria detection. *Journal of Hazardous Materials*, 454, 131485. <https://doi.org/10.1016/j.jhazmat.2023.131485>
- Lin, J., & Brown, C. W. (1997). Sol-gel glass as a matrix for chemical and biochemical sensing. *TRAC Trends in Analytical Chemistry*, 16(4), 200–211. [https://doi.org/10.1016/s0165-9936\(97\)00021-6](https://doi.org/10.1016/s0165-9936(97)00021-6)
- Lin, F., Li, C., Dong, L., Fu, D., & Chen, Z. (2017). Imaging biofilm-encased microorganisms using carbon dots derived from *L. plantarum*. *RSC Nanoscale*, 9, 9056–9064. <https://doi.org/10.1039/C7NR01975K>
- Lin, F., Li, C., & Chen, Z. (2018). Bacteria-derived carbon dots inhibit biofilm formation of *Escherichia coli* without affecting cell growth. *Frontiers in Microbiology*, 9, 259. <https://doi.org/10.3389/fmicb.2018.00259>
- Lindsay, C. A., Kinghorn, A. D., & Rakotondraibe, H. L. (2023). Bioactive and unusual steroids from *Penicillium* fungi. *Phytochemistry*, 209, 113638. <https://doi.org/10.1016/j.phytochem.2023.113638>
- Lopes, A. T. S., Albuquerque, G. R., & Maciel, B. M. (2018). Multiplex real-time polymerase chain reaction for simultaneous quantification of *Salmonella* spp., *Escherichia coli*, and *Staphylococcus aureus* in different food matrices: Advantages and disadvantages. *BioMed Research International*, 2018, 1–12. <https://doi.org/10.1155/2018/6104015>
- Luo, H., Wang, G., Chen, N., Fang, Z., Xiao, Y., Zhang, M., Gerelt, K., Qian, Y., Lai, R., & Zhou, Y. (2022). A superefficient ochratoxin A hydrolase with promising potential for industrial applications. *Applied and Environmental Microbiology*, 88(2), e0196421.
- Ma, B., Li, J., Chen, K., Yu, X., Sun, C., & Zhang, M. (2020). Multiplex recombinase polymerase amplification assay for the simultaneous detection of three foodborne pathogens in seafood. *Food*, 9(3), 278. <https://doi.org/10.3390/foods9030278>
- Mädler, L., Kammler, H., Mueller, R., & Pratsinis, S. (2002). Controlled synthesis of nanostructured particles by flame spray pyrolysis. *Journal of Aerosol Science*, 33(2), 369–389. [https://doi.org/10.1016/s0021-8502\(01\)00159-8](https://doi.org/10.1016/s0021-8502(01)00159-8)
- Makhluף, S., Dror, R., Nitzan, Y., Abramovich, Y., Jelinek, R., & Gedanken, A. (2005). Microwave-assisted synthesis of nanocrystalline MGO and its use as a bactericide. *Advanced Functional Materials*, 15(10), 1708–1715. <https://doi.org/10.1002/adfm.200500029>
- Manusuriya, B. D., & Altintas, Z. (2021). Carbon dots: Classification, properties, synthesis, characterization, and applications in health care—An updated review (2018–2021). *Nanomaterials*, 11(10), 2525. <https://doi.org/10.3390/nano11102525>
- Marien, C. B. D., Marchal, C., Koch, A., Robert, D., & Drogui, P. (2016). Sol-gel synthesis of TiO₂ nanoparticles: Effect of Pluronic P123 on particle's morphology and photocatalytic degradation of paraquat. *Environmental Science and Pollution Research*, 24(14), 12582–12588. <https://doi.org/10.1007/s11356-016-7681-2>

- Martínez-Perinan, E., García-Mendiola, T., Enebral-Romero, E., Del Cano, R., Vera-Hidalgo, M., Sulleiro, M. V., et al. (2021). A MoS₂ platform and thionine-carbon nanodots for sensitive and selective detection of pathogens. *Biosensors and Bioelectronics*, 189, 113375. <https://doi.org/10.1016/j.bios.2021.113375>
- Martínez-Periñán, E., Martínez-Sobrino, Á., Bravo, I., García-Mendiola, T., Mateo-Martí, E., Pariente, F., & Lorenzo, E. (2022). Neutral red-carbon nanodots for selective fluorescent DNA sensing. *Analytical and Bioanalytical Chemistry*, 414(18), 5537. <https://doi.org/10.1007/s00216-022-03980-1>
- Nadzirah, S., Hashim, U., Gopinath, S. C. B., Parmin, N. A., Hamzah, A. A., Yu, H. W., & Dee, C. F. (2020). Titanium dioxide-mediated resistive nanobiosensor for E. coli O157:H7. *Microchimica Acta*, 187(4), 235. <https://doi.org/10.1007/s00604-020-4214-y>
- Navale, V., Vamkudoth, K. R., Ajmera, S., & Dhuri, V. (2021). Aspergillus derived mycotoxins in food and the environment: Prevalence, detection, and toxicity. *Toxicology Reports*, 8, 1008–1030. <https://doi.org/10.1016/j.toxrep.2021.04.013>
- Nayab, D., & Akhtar, S. (2023). Green synthesized silver nanoparticles from eucalyptus leaves can enhance shelf life of banana without penetrating in pulp. *PLoS One*, 18(3), e0281675. <https://doi.org/10.1371/journal.pone.0281675>
- Omar, S. S. (2016). Aflatoxin M1 levels in raw milk, pasteurised milk and infant formula. *Italian Journal of Food Safety*, 5(3), 5788. <https://doi.org/10.4081/ijfs.2016.5788>
- Oves, M., Rauf, M. A., Aslam, M., Qari, H. A., Sonbol, H., Ahmad, I., Zaman, G. S., & Saeed, M. (2022). Green synthesis of silver nanoparticles by Conocarpus Lancifolius plant extract and their antimicrobial and anticancer activities. *Saudi Journal of Biological Sciences*, 29(1), 460–471. <https://doi.org/10.1016/j.sjbs.2021.09.007>
- Pal, T., Mohiyuddin, S., & Packirisamy, G. (2018). Facile and green synthesis of multicolor fluorescence carbon dots from curcumin: In vitro and in vivo bioimaging and other applications. *ACS Omega*, 3, 831–843. <https://doi.org/10.1021/acsomega.7b01323>
- Paterson, R., & Lima, N. (2017). Filamentous fungal human pathogens from food emphasising aspergillus, fusarium and mucor. *Microorganisms*, 5(3), 44. <https://doi.org/10.3390/microorganisms5030044>
- Patil, T. P., Vibhute, A. A., Patil, S. L., Dongale, T. D., & Tiwari, A. P. (2023). Green synthesis of gold nanoparticles via Capsicum annum fruit extract: Characterization, antiangiogenic, antioxidant and anti-inflammatory activities. *Applied Surface Science Advances*, 13, 100372. <https://doi.org/10.1016/j.apsadv.2023.100372>
- Piacentini, K. C., Rocha, L. O., Savi, G. D., Carnielli-Queiroz, L., De Carvalho Fontes, L., & Correa, B. (2019). Assessment of toxigenic fusarium species and their mycotoxins in brewing barley grains. *Toxins*, 11(1), 31. <https://doi.org/10.3390/toxins11010031>
- Pourmadadi, M., Yazdian, F., Hojjati, S., & Khosravi-Darani, K. (2021). Detection of microorganisms using graphene-based nanobiosensors. *Food Technology and Biotechnology*, 59(4), 496–506. <https://doi.org/10.17113/ftb.59.04.21.7223>
- Pugazhenthiran, N., Anandan, S., Kathiravan, G., Prakash, N. K. U., Crawford, S., & Ashokkumar, M. (2009). Microbial synthesis of silver nanoparticles by Bacillus sp. *Journal of Nanoparticle Research*, 11(7), 1811–1815. <https://doi.org/10.1007/s11051-009-9621-2>
- Qi, W., Zheng, L., Wang, S., Huang, F., Liu, Y., Jiang, H., & Lin, J. (2021). A microfluidic biosensor for rapid and automatic detection of salmonella using metal-organic framework and Raspberry Pi. *Biosensors and Bioelectronics*, 178, 113020. <https://doi.org/10.1016/j.bios.2021.113020>
- Ren, J., Liang, G., Man, Y., Li, A., Jin, X., Liu, Q., & Pan, L. (2019). Aptamer-based fluorometric determination of salmonella typhimurium using Fe₃O₄ magnetic separation and CdTe quantum dots. *PLoS One*, 14(6), e0218325. <https://doi.org/10.1371/journal.pone.0218325>
- Ritenberg, M., Nandi, S., Kolusheva, S., Dandela, R., Meijler, M. M., & Jelinek, R. (2016). Imaging Pseudomonas aeruginosa biofilm extracellular polymer scaffolds with amphiphilic carbon dots. *ACS Chemical Biology*, 11(5), 1265–1270. <https://doi.org/10.1021/acscchembio.5b01000>

- Rodrigues, M. H. P., Marques, C. G., De Almeida Senna, C., Cerqueira, M. B. R., Kupski, L., & Furlong, E. B. (2022). Patulin in tomatoes and the inhibitory capacity of their phenolic extracts against *Penicillium expansum*. *Food Research International*, 162, 112085. <https://doi.org/10.1016/j.foodres.2022.112085>
- Savas, S., & Altıntaş, Z. (2019). Graphene quantum dots as nanozymes for electrochemical sensing of *Yersinia enterocolitica* in milk and human serum. *Materials*, 12(13), 2189. <https://doi.org/10.3390/ma12132189>
- Schmidt-Heydt, M., Stoll, D., & Geisen, R. (2019). Whole-genome sequencing of the fungus *penicillium citrinum* reveals the biosynthesis gene cluster for the mycotoxin citrinin. *Microbiology Resource Announcements*, 8(4), e01419-18. <https://doi.org/10.1128/mra.01419-18>
- Schrenk, D., Bodin, L., Chipman, J. K., Del Mazo, J., Grasl-Kraupp, B., Hogstrand, C., Hoogenboom, L., Leblanc, J., Nebbia, C. S., Nielsen, E., Ntzani, E., Petersen, A., Sand, S., Schwerdtle, T., Vlemminckx, C., Wallace, H., Alexander, J., Dall'Asta, C., Mally, A., et al. (2020). Risk assessment of ochratoxin A in food. *EFSA Journal*, 18(5), e06113. <https://doi.org/10.2903/j.efsa.2020.6113>
- Shahverdi, A. R., Minaeian, S., Shahverdi, H. R., Jamalifar, H., & Nohi, A. (2007). Rapid synthesis of silver nanoparticles using culture supernatants of enterobacteria: A novel biological approach. *Process Biochemistry*, 42(5), 919–923. <https://doi.org/10.1016/j.procbio.2007.02.005>
- Sohrabi, H., Majidi, M. R., Asadpour-Zeynali, K., Khataee, A., & Mokhtarzadeh, A. (2022). Bimetallic Fe/Mn MOFs/MβCD/AuNPs stabilized on MWCNTs for developing a label-free DNA-based genosensing bio-assay applied in the determination of *Salmonella typhimurium* in milk samples. *Chemosphere*, 287, 132373. <https://doi.org/10.1016/j.chemosphere.2021.132373>
- Su, Z., Du, T., Liang, X., Wang, X., Zhao, L., Sun, J., Wang, J., & Zhang, W. (2022). Nanozymes for foodborne microbial contaminants detection: Mechanisms, recent advances, and challenges. *Food Control*, 141, 109165. <https://doi.org/10.1016/j.foodcont.2022.109165>
- Sundramoorthy, A. K., Vignesh Kumar, T. H., & Gunasekaran, S. (2018). Graphene-based nanosensors and smart food packaging systems for food safety and quality monitoring. In *Graphene bioelectronics* (pp. 267–306). Elsevier. <https://doi.org/10.1016/B978-0-12-813349-1.00012-3>
- Sunkar, S., & Nachiyar, C. V. (2012). Biogenesis of antibacterial silver nanoparticles using the endophytic bacterium *Bacillus cereus* isolated from *Garcinia xanthochymus*. *Asian Pacific Journal of Tropical Biomedicine*, 2(12), 953–959. [https://doi.org/10.1016/s2221-1691\(13\)60006-4](https://doi.org/10.1016/s2221-1691(13)60006-4)
- Sur, U. K., Ankamwar, B., Karmakar, S., Halder, A., & Das, P. (2018). Green synthesis of silver nanoparticles using the plant extract of Shikakai and Reetha. *Materials Today Proceedings*, 5(1), 2321–2329. <https://doi.org/10.1016/j.matpr.2017.09.236>
- Suriyakala, G., Sathiyaraj, S., Babujanathanam, R., Alarjani, K. M., Hussein, D. S., Rasheed, R. A., & Kanimozhi, K. (2022). Green synthesis of gold nanoparticles using *Jatropha integerrima* Jacq. flower extract and their antibacterial activity. *Journal of King Saud University, Science*, 34(3), 101830. <https://doi.org/10.1016/j.jksus.2022.101830>
- Swain, K. K., & Bhand, S. (2021). A colorimetric paper-based ATONP-ALP nanobiosensor for selective detection of Cd²⁺ ions in clams and mussels. *Analytical and Bioanalytical Chemistry*, 413(6), 1715–1727. <https://doi.org/10.1007/s00216-020-03140-3>
- Talekar, S., Joshi, A., Chougale, R., Nakhe, A., & Bhojwani, R. (2016). Immobilized enzyme mediated synthesis of silver nanoparticles using cross-linked enzyme aggregates (CLEAs) of NADH-dependent nitrate reductase. *Nano-Structures & Nano-Objects*, 6, 23–33. <https://doi.org/10.1016/j.nanos.2016.03.002>
- Tang, Z., Liu, X., Su, B., Chen, Q., Cao, H., Yun, Y., Xu, Y., & Hammock, B. D. (2020). Ultrasensitive and rapid detection of ochratoxin A in agro-products by a nanobody-mediated FRET-based immunosensor. *Journal of Hazardous Materials*, 387, 121678. <https://doi.org/10.1016/j.jhazmat.2019.121678>

- Thakur, M., Wang, B., & Verma, M. L. (2022). Development and applications of nanobiosensors for sustainable agricultural and food industries: Recent developments, challenges and perspectives. *Environmental Technology & Innovation*, 26, 102371. <https://doi.org/10.1016/j.eti.2022.102371>
- Tsai, H. W., Wu, T., Hsieh, C. L., Fu, S. F., Wud, M. Y., & Lin, Y. W. (2023). Green synthesis of gardenia seeds-based carbon dots for bacterial imaging and antioxidant activity in aqueous and oil samples. *RSC Advances*, 13, 29283–29290. <https://doi.org/10.1039/D3RA06293G>
- USDA. (2024). *World food safety day spotlights global health threat*. Retrieved July 21, 2024, from <https://www.usda.gov/media/blog/2022/06/07/world-food-safety-day-spotlights-global-health-threat>
- Uskokovic, V., & Drofenik, M. (2005). Synthesis of materials within reverse micelles. In Jožef Stefan Institute & Faculty of Chemistry and Chemical Engineering (Ed.), *Surface review and letters* (Vol. 12, pp. 239–277). World Scientific Publishing Company.
- Valenzuela-Amaro, H. M., Aguayo-Acosta, A., Meléndez-Sánchez, E. R., de la Rosa, O., Vázquez-Ortega, P. G., Oyervides-Muñoz, M. A., Sosa-Hernández, J. E., & Parra-Saldívar, R. (2023). Emerging applications of nanobiosensors in pathogen detection in water and food. *Biosensors*, 13(10), 10. <https://doi.org/10.3390/bios13100922>
- Viter, R., Tereshchenko, A., Smyntyna, V., Ogorodniichuk, J., Starodub, N., Yakimova, R., Khranovskyy, V., & Ramanavicius, A. (2017). Toward development of optical biosensors based on photoluminescence of TiO₂ nanoparticles for the detection of salmonella. *Sensors and Actuators B: Chemical*, 252, 95–102. <https://doi.org/10.1016/j.snb.2017.05.139>
- Wang, H., Qiao, X., Chen, J., Wang, X., & Ding, S. (2005). Mechanisms of PVP in the preparation of silver nanoparticles. *Materials Chemistry and Physics*, 94(2–3), 449–453. <https://doi.org/10.1016/j.matchemphys.2005.05.005>
- Wang, N., Wang, Y., Guo, T., Yang, T., & Chen, M. (2016). Green preparation of carbon dots with papaya as carbon source for effective fluorescent sensing of iron (III) and Escherichia coli. *Biosensors and Bioelectronics*, 85, 68–75. <https://doi.org/10.1016/j.bios.2016.04.089>
- Wang, H., Wang, L., Hu, Q., Wang, R., Li, Y., & Kidd, M. (2018). Rapid and sensitive detection of *Campylobacter jejuni* in poultry products using a nanoparticle-based piezoelectric immunosensor integrated with magnetic immunoseparation. *Journal of Food Protection*, 81(8), 1321–1330. <https://doi.org/10.4315/0362-028x.jfp-17-381>
- Wang, L., Huo, X., Qi, W., Xia, Z., Li, Y., & Lin, J. (2020a). Rapid and sensitive detection of *Salmonella typhimurium* using nickel nanowire bridge for electrochemical impedance amplification. *Talanta*, 211, 120715. <https://doi.org/10.1016/j.talanta.2020.120715>
- Wang, Y., Schill, K. M., Fry, H. C., & Duncan, T. V. (2020b). A quantum dot Nanobiosensor for rapid detection of botulinum neurotoxin serotype E. *ACS Sensors*, 5(7), 2118–2127. <https://doi.org/10.1021/acssensors.0c00738>
- Wang, L., Hua, X., Shi, J., Jing, N., Ji, T., Lv, B., Liu, L., & Chen, Y. (2022). Ochratoxin A: Occurrence and recent advances in detoxification. *Toxicon*, 210, 11–18. <https://doi.org/10.1016/j.toxicon.2022.02.010>
- Weng, X., & Neethirajan, S. (2016). A microfluidic biosensor using graphene oxide and aptamer-functionalized quantum dots for peanut allergen detection. *Biosensors and Bioelectronics*, 85, 649–656. <https://doi.org/10.1016/j.bios.2016.05.072>
- Weng, X., Zhang, C., & Jiang, H. (2021). Advances in microfluidic nanobiosensors for the detection of foodborne pathogens. *LWT*, 151, 112172. <https://doi.org/10.1016/j.lwt.2021.112172>
- Wu, Q., Wu, W., Franca, T. C., Jacevic, V., Wang, X., & Kuca, K. (2018). Immune evasion, a potential mechanism of trichothecenes: New insights into negative immune regulations. *International Journal of Molecular Sciences*, 19(11), 3307.
- Xu, L., Fang, G., Pan, M., Wang, X., & Wang, S. (2015). One-pot synthesis of carbon dots-embedded molecularly imprinted polymer for specific recognition of sterigmatocystin in grains. *Biosensors and Bioelectronics*, 77, 950–956. <https://doi.org/10.1016/j.bios.2015.10.072>
- Xue, L., Jin, N., Guo, R., Wang, S., Qi, W., Liu, Y., Li, Y., & Lin, J. (2021). Microfluidic colorimetric biosensors based on MnO₂ nanozymes and convergence–divergence spiral

- micromixers for rapid and sensitive detection of *Salmonella*. *ACS Sensors*, 6(8), 2883–2892. <https://doi.org/10.1021/acssensors.1c00292>
- Yao, Y., Hou, L., Wei, F., Lin, T., & Zhao, S. (2024). An intelligent readable and capture-antibody-independent lateral flow immunoassay based on Cu₂-xSe nanocrystals for point-of-care detection of *Escherichia coli* O157:H7. *The Analyst*, 149(2), 357–365. <https://doi.org/10.1039/d3an01694c>
- Zhang, H., Li, Q., Lu, Y., Sun, D., Lin, X., Deng, X., He, N., & Zheng, S. (2004). Biosorption and bioreduction of diamine silver complex by *Corynebacterium*. *Journal of Chemical Technology & Biotechnology*, 80(3), 285–290. <https://doi.org/10.1002/jctb.1191>
- Zhao, Y., Li, Y., Zhang, P., Yan, Z., Zhou, Y., Du, Y., Qu, C., Song, Y., Zhou, D., Qu, S., & Yang, R. (2021). Cell-based fluorescent microsphere incorporated with carbon dots as a sensitive immunosensor for the rapid detection of *Escherichia coli* O157 in milk. *Biosensors and Bioelectronics*, 179, 113057. <https://doi.org/10.1016/j.bios.2021.113057>
- Zheng, F., Wang, P., Du, Q., Chen, Y., & Liu, N. (2019a). Simultaneous and ultrasensitive detection of foodborne bacteria by gold nanoparticles-amplified microcantilever array biosensor. *Frontiers in Chemistry*, 7, 232. <https://doi.org/10.3389/fchem.2019.00232>
- Zheng, L., Cai, G., Qi, W., Wang, S., Wang, M., & Lin, J. (2019b). Optical biosensor for rapid detection of *Salmonella typhimurium* based on porous gold@platinum nanocatalysts and a 3D fluidic chip. *ACS Sensors*, 5(1), 65–72. <https://doi.org/10.1021/acssensors.9b01472>
- Zhou, S., Lu, C., Li, Y., Xue, L., Zhao, C., Tian, G., Bao, Y., Tang, L., Lin, J., & Zheng, J. (2020). Gold nanobones enhanced ultrasensitive surface-enhanced Raman scattering Aptasensor for detecting *Escherichia coli* O157:H7. *ACS Sensors*, 5(2), 588–596. <https://doi.org/10.1021/acssensors.9b02600>
- Zorraquín-Peña, I., Cueva, C., Bartolomé, B., & Moreno-Arribas, M. V. (2020). Silver nanoparticles against foodborne bacteria. Effects at intestinal level and health limitations. *Microorganisms*, 8(1), 132. <https://doi.org/10.3390/microorganisms8010132>

Chapter 3

Nanomaterials in Pesticide Detection and Degradation



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Abstract Farmers have long relied on pesticides for pest management, including insecticides, fungicides, and herbicides. Increasingly we see alternative farming practices and the integration of pesticides into pest management programs. However, pesticide use remains critical for world food production and pesticide persistence in the environment and toxicity can also cause risks to human health and the environment. This chapter will explore the difficulties of using conventional methods for detecting this pesticide, which is accurate and selective but complicated enough often to need complex procedures, expensive and fragile equipment and expert knowledge. Modern pesticides are increasingly biodegradable but there are still problems with historical contamination and slow environmental degradation of many pesticides. Therefore, continued research is needed to develop efficient, cost-effective, ecofriendly techniques for detection and remediation of pesticide residues. This review will illustrate how nanotechnology helps deal with those shortcomings by employing nanomaterials for rapid detection and effective removal and degradation of pesticide traces in several environmental matrices. This article also discusses how nanomaterials-based approaches tackle pesticide pollution problems with high sensitivity and precision. Within the scope of this discussion is the role of nanotechnology in making our environment safe and decreasing health effects related to pesticides.

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Keywords Pesticide detection and determination · Nanobody based immunoassay · Nanomaterial based sensors · Pesticide removal and degradation · Nanotechnology approaches

3.1 Introduction

Nanomaterials are a broad category of materials at nanoscale level with sizes ranging from 1 to 100 nm. Compared to their bulk equivalents, these particles have unique chemical, biological, and physical characteristics. These characteristics of NPs may be related to their tiny size, distinct form, and higher surface area (Khan et al., 2019). In the last few years, scientists have explored many avenues related to nanotechnology to boost agricultural production rates and enhance food processing mechanisms. Nanoparticles transfer nutrients into plants, synthesize nano formulated pesticides, and develop nanosensors that identify pesticide and remediation agents for pesticides (Bratovic et al., 2023). The use of nanotechnology for degradation of pesticides has been on the rise (Rawtani et al., 2018). Pesticides, which include insecticides, fungicides, and herbicides, are defined by the Environmental Protection Agency (EPA) as substances or mixtures of substances meant for killing, repelling, and preventing pests (Yadav & Devi, 2017). Although the highly persistent organic chemicals with half lives of many years largely have been phased out, some pesticides are long lived particularly in microenvironments that retard degradation. In agricultural farms, they have been widely employed to manage pests such as fungi, insects, and microbes, hence can improve crop productivity, safety and profitability (Rani et al., 2017). In spite of many advances including the rapid spread of integrated pest control techniques, pesticides remain a major tool in agriculture for managing pests, even with a commitment to integrated pest management pesticides are a major tool in world food production. In the previous century, pesticides were the most widely disseminated chemical contaminants in the environment. The earlier pesticides were classified into four major groups, determined by their structures: carbamates, organochlorines, pyrethroids, and organophosphates (Yadav & Devi, 2017). The toxic nature of pesticides and their inability to biodegrade have become severe risks to the ecosystem and human health (Rasheed et al., 2021). The wide application and overuse of pesticides, as well as their specific chemical structures, pesticides are dangerous substances that can damage ecosystems as they affect the surroundings and get into the food chain (El-Sheikh & Ashour, 2010; El-Sheikh et al., 2023). Furthermore, even at low concentrations of pesticides, there can be adverse effects (Islam et al., 2022). Thus, the identification, removal and degradation of pesticides has been a main challenge.

Consequently, many studies have been focused on techniques for the identification and breaking down of pesticides (Fazeli-Nasab et al., 2022). There are many common analytical and quantitative methods used to determine and identify pesticide residues, such as Gas Chromatography (GC), High Performance Liquid Chromatography (HPLC), Liquid Chromatography (LC), Liquid Chromatography Mass Spectrometer (LC-MS/MS), Gas Chromatography Mass Spectrometer (GC-MS),

and immunoassay (Hammock & Mumma, 1980; Vasylieva et al., 2015; Fazeli-Nasab et al., 2022; Thorat et al., 2023; Gao et al., 2024). LC and GLC MS have many advantages, including selectivity, accuracy, and sensitivity and generally are considered the ‘gold standard’ for analytical chemistry. Despite these advantages, they are sequential techniques handling one sample at a time when many of our environmental problems are better solved by massively parallel analytical approaches which can monitor multiple samples at one time. Most mass spectrometry-based technologies are not suitable for rapid detection and typically require trained individuals to operate and tiresome steps, including pretreatment of samples and purification. Maintenance of such equipment is expensive and sometimes finding the infrastructure, technical knowledge and parts to main the equipment is difficult in remote areas.

Pesticide detection has greatly improved due to the advancement of detectors based on nanotechnology (Gamage et al., 2024). Herein, this chapter discusses the diverse roles of numerous kinds of nanomaterials along with their application in detecting various pesticide residues from diverse environmental samples. In addition, we discuss various recently applied strategies for pesticide removal and degradation.

3.2 Advanced Techniques for Detection of Pesticides

Many researchers have tried hard to investigate several modern techniques, and they turned out to be successful after the application of these methods. There are numerous advanced methods such as sensors, automation, machine learning algorithms and artificial intelligence to identify the type of pesticide and its concentration. One common way of detecting pesticide residue is biosensors. Nevertheless, it’s necessary to do a lot of training in the module of machine learning and artificial intelligence in different conditions, which makes their applications restricted as far as this goes (Thorat et al., 2023). However, this can be achieved somehow. Various advanced techniques for pesticide residues identification are shown in Table 3.1.

3.3 Nanomaterials for Pesticide Detection

3.3.1 *Nanobodies Based Immunoassay*

After the 1977 Nobel Prize to Rosylin Yallow for immunoassay, technology made rapid headway in medical applications and particularly in point of care and high throughput analysis in clinical settings. Only later was this technology applied to analysis of environmental and human health samples related to pesticides (Wing et al., 1978; Hammock & Mumma, 1980; Gonzalez-Techera et al., 2007) Nowadays, pesticide detection based on enzyme-linked immunosorbent assay (ELISA) is the

Table 3.1 Advanced techniques for pesticide detection

Techniques	Examples of detected pesticide	Advantages	Disadvantages	References
Hyperspectral imaging sensor	Chorpyrifos	Due to their high spectral resolution, the target characteristics of the object can be identified and distinguished.	The device's complexity and cost	Jiang et al. (2017)
Back propagation neural network analysis of fluorescence spectra	Acetamiprid	Reduced measuring time, excellent accuracy, and rapid training speed	It is not suitable for detecting multiple pesticides with overlapped fluorescence intensities.	Bian et al. (2020)
Integrated platform	Organophosphate and carbamate	Detection of different parameters in a specific system	Large setup size and cost	Moldovan et al. (2017), Mejula et al. (2020)
Electrochemical sensor	Methyl parathion, paraoxon, and dichlorvos	Greater accuracy, less expensive than other sensors, and high reproducibility	The restricted range of temperature resistance, short working period, and utilization of multianalyte detection is limited.	Hara and Singh (2021)
Embedded system	Organophosphate	Low expenses, steadiness, simplicity	The possibility of memory loss and overload condition resets.	Arduini et al. (2015), Saran et al. (2024)

most widespread heterogeneous immunoassay. Three reagents are required for this method: an immunosorbent, which is an antibody or antigen coated on the solid phase; enzyme conjugates, which are antibodies or antigens tagged with enzymes; and a chromogenic agent for the enzymatic color reaction (Xu et al., 2022). Antibodies, also known as immunoglobulins (Igs), are large proteins that B cells produce in reaction to antigens. The Y-shaped structure of the antibody results from inter- and intra-disulfide bonds between the two light chains and two heavy chains, which have a molecular weight of about 150 kDa (Fig. 3.1).

Polyclonal assays still dominate the field because of the low cost of production and use as well as the high sensitivity of reagents generated by immune maturation. However, only a single pool of antibodies can be certified. Larger animals or pools of multiple bleeds can be used but ultimately this pool will be exhausted. Monoclonal antibodies traditionally from mice served as the basis to circumvent this problem. However, even monoclonal antibodies can be lost due to freezer or other failures.

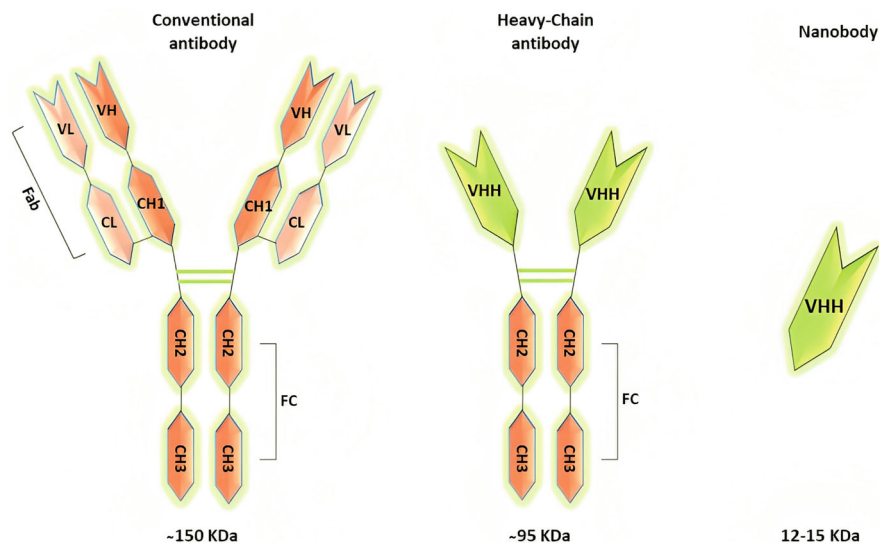


Fig. 3.1 Schematic illustration showing the conventional antibody, heavy chain antibody, and nanobodies with their molecular weights

Polyclonal antibodies can vary significantly between individuals and over time within the same individual. Consequently, they are less reliable and accurate analytical methods, as mentioned above only a single pool can be certified. Polyclonal antibodies are technically cheaper, faster to manufacture, and often more sensitive than monoclonal antibodies. However, the availability of a single, highly selective antibody in a nearly limitless supply is highly advantageous (Bever et al., 2014). Köhler and Milstein (1975) introduced monoclonal antibodies that eliminated the molecular recognition fluctuations associated with Polyclonal antibody analysis. In spite of common losses of the clones monoclonal antibodies often still are regarded as the best bio-recognition molecules for immunoassays in regulatory environments. However, the widely used ZM7B2 monoclonal antibody for atrazine analysis was ultimately lost in spite of being stored in separate locations around the world.

A new type of antibody, called Heavy chain antibody only, was discovered in 1993. These antibodies most commonly are produced from camelids or shark blood because these animals produce heavy chain only antibodies naturally. They lack a light chain, and thus only attach to antigens on the heavy chain's variable domain (VHH) (Fig. 3.1). This VHH, commonly known as nanobodies (Nbs), Often has very high affinity for their target antigen. The name "nanobodies" was coined due to the small size of VHH in the low nanometer scale (measuring $4 \times 2.5 \times 3$ nm), with molecular weight approximately one-tenth that of a conventional antibody. In addition, they are highly stable, very soluble, exhibit low immunogenicity response due to difficult recognition by different epitopes, penetrate tissues, and can be produced on an industrial scale (Su et al., 2023). They can be engineered with simple gene manipulation to add binding and recognition domains. VHHs can be

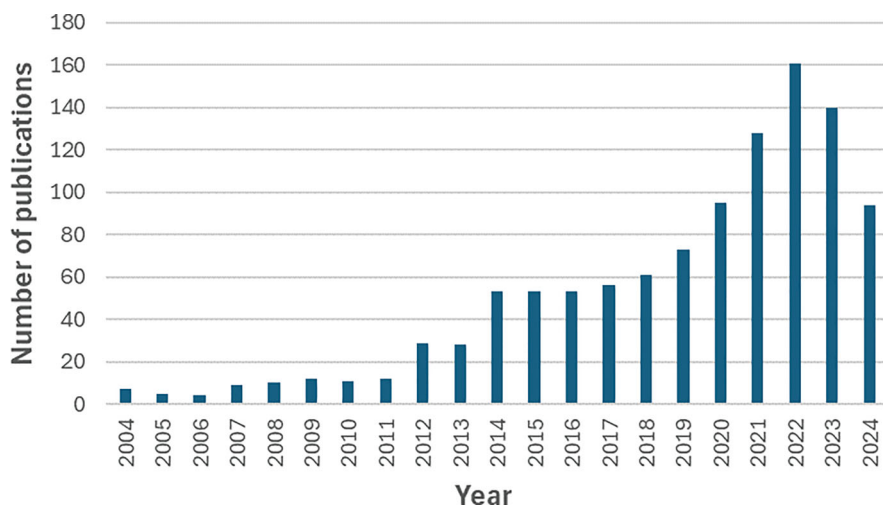


Fig. 3.2 Bar chart showing the number of scientific publications per year on the use of nanobodies for detection. (From PubMed database, 8/2/2024)

readily expressed in a variety of expression systems and are accessible to genetic manipulation due to their nature (Harmsen & De Haard, 2007). It was discovered naturally, and due to advances in molecular engineering, prokaryotic cultures may now express VHHs, opening up new avenues for developing antibodies with characteristics such as monoclonality, high throughput screening, and in vitro persistence (Bever et al., 2014). Figure 3.2 illustrates a rise in the number of publications about using nanobodies for detection during the last few years.

The generation of nanobody is shown in Fig. 3.3. Initially, individual camelids are immunized with the antigen. However, small molecules weighing less than 1000 kDa, known as haptens, need to be bonded to carrier proteins to be presented to the immune system and stimulate an immune response just as with classical antibodies. This large size is of course required for all classical antibody production to recognize haptens or small molecules. Next, the peripheral blood is collected. Heavy chain antibodies have their mRNA extracted, then reverse-transcribed to obtain cDNA for cloning into a phagemid vector, effectively generating a phage display library. Nanobodies that recognize the pesticides have been identified through biopanning done in tightly controlled conditions (Bever et al., 2014; Su et al., 2023). Examples of nanobodies used in immunoassay detection of pesticides are provided in Table 3.2.

3.3.2 Nanomaterials Based Sensors

Nano-based technologies were found to have several applications in different pesticide detection methods, including nano biosensor, nano electrochemical sensors,

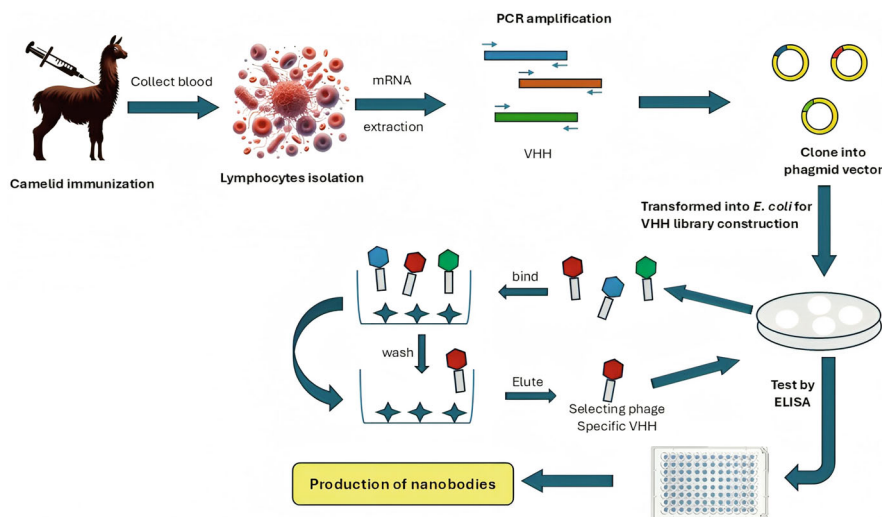


Fig. 3.3 Schematic of nanobody generation from an immunized display library

and nano optical sensors (Gamage et al., 2024). These sensors based on nanoparticles stand out from traditional spectrophotometric analytic methods because they possess high sensitivity, low detection limits and are simple to use (Zhang et al., 2023a). Table 3.2 summarizes various nanomaterials-based sensors used in detection of pesticides. Sometimes separate technological innovations can synergize technological improvements. Taking advantage of new sensor technologies and microelectronics can make immunochemical based sensors potentially very valuable. However, a major engineering effort to develop a sensor system around a single antibody would not be cost effective if that antibody could be lost. The fact that nanobody sequences can be sent around the world electronically means that the nanobodies are in fact immortal and can be recovered in the future. This in turn encourages technological development of sensors around a specific nanobody. Thus the sensor and the nanobody technologies are synergizing development in parallel.

3.3.2.1 Optical Sensors

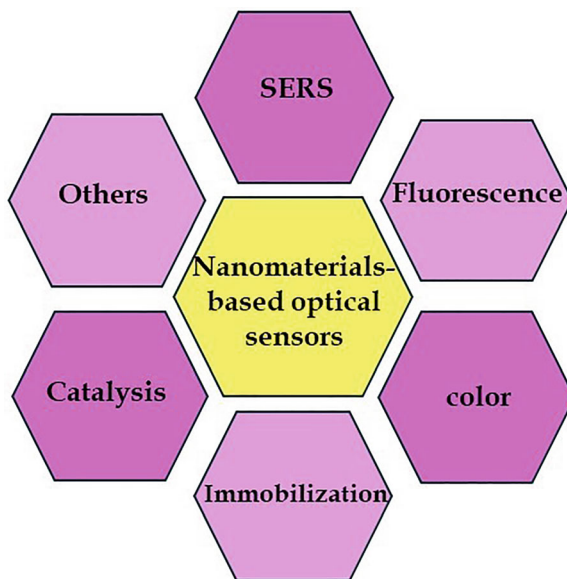
Nanoparticles provide a different function in pesticide detection, including catalysis, SERS, fluorescence enhancement, and color change. Figure 3.4 summarizes their application to the detection of pesticides (Zhang et al., 2023a). Various techniques have been used in optical sensing including metal nanoparticles, carbon dots, and quantum dots. Additionally, an innovative type of fluorescent material with enormous possibilities in the optical sensing area is emerging which comprises aptasensors built on nanoparticles, antibodies, metal-organic frameworks, aggregation-induced emission, ratiometric fluorescence nanoprobe, fluorescent

Table 3.2 Various nanomaterials used for detection of pesticides

Detection method	Nanomaterial	Target pesticides	Sample type	Reference
Immunoassay	Mesoporous silicon nanospheres	Avermectin	Food	Ji et al. (2020)
	Magnetic nanoparticles	Dchlorvos and paraoxon	Milk	Yaneva et al. (2018)
	AuNPs and upconversion nanoparticles	Acetamiprid	Apple and cucumber	Li et al. (2021a)
	Pt-Ni(OH) ₂ nanosheets	Acetochlor and fenpropathrin	Water, cabbage, spiked corn, and apple	Cheng et al. (2019)
	Nanobody	Cytraniliprole and chlorantraniliprole	Soil and bok choy	Xu et al. (2021)
	Bispecific nanobody	The metabolite 1-naphthol and carbaryl	Rice and soil	Liu et al. (2023)
	Nanobody	Herbicide 2,4-dichlorophenoxyacetic acid	Water	Li et al. (2021b)
	Nanobody-alkaline phosphatase fusion protein	3-Phenoxybenzoic acid (pyrethroids metabolite)		Huo et al. (2018)
	Magnetic nanoparticles and upconversion nanoparticles	Imidacloprid and thiacloprid	Soil, pears, cucumbers, oranges, wheat, and paddy water,	Tao et al. (2019)
	Nanobody	3-Phenoxybenzoic acid		El-Moghazy et al. (2020)

Sensors	MTZ-AgNPs	Permethrin	Apple and tomato	Rasheed et al. (2023),
	Ag nano-dendrite optical fiber	Permethrin		Pham et al. (2019)
	UCNPs@ZIF-8@MIPs	alpha-cypermethrin	Pear, cabbage, and apple	Hu et al. (2020)
	Nano-iron oxyhydroxide	Carbendazim	Apple juice	Yang et al. (2024)
	AuNPs	Paraquat	Soil extracts, drinking water, agri-water, tap water, and environmental water	Botta et al. (2020)
	CoS-NPs attached ZnS rods (CoS/ZnS composites)	Chloroneb	Soil, river water, licorice, and cucumber	Duan et al. (2021)
	Au nanospikes on magnetic microparticles (using Ag nanoparticle-modified magnetic microparticles as a template)	Thiram	Soil	Zou et al. (2022)
	Au@4-MBA@Ag nanoparticle array	Thiabendazole and thiram	Organic and aqueous phases	Wang and Li (2021)
	AgNPs	Tribenuron-methyl	Water and soil	Kamyabi and Moharramzha (2021)
	AuNPs	Thiram	Soil and apple	Liu et al. (2022a)
	Carbon nanoparticles	Methyl parathion	Soil	Sanghavi et al. (2012)
	AuNP probe	Glyphosate	Food samples	Guan et al. (2021)
	FL@SPIONs@MIP	Imidacloprid	Water, soil, fruit juice, and vegetable extracts	Kumar et al. (2018)
	AP-algae-modified ZnO nanoparticles	Chlorpyrifos	Soil	Pabbi et al. (2018)

Fig. 3.4 Application of nanomaterials-based optical sensors for pesticides identification



molecular imprinted polymers, paper-based analytical devices, photoluminescence metal-organic frameworks, electrochemiluminescence sensors and fluorescent probe based on cucurbit[n]urils. Several fluorescent-based nanosensors have been investigated for pesticide monitoring. The following reasons are why upconversion nanoparticles were preferred as fluorescent biolabels compared to conventional organic fluorophores; they possess appealing optical and chemical attributes, plus the ability not to be affected by photobleaching or blinking, nor can they undergo any form of photochemical degradation (Gyanjyoti et al., 2023). Methyl parathion detection in rice samples was conducted using a sensitive fluorescent sensing system that uses a new carbon quantum dots nano-fluorescent probe based on a corn stalk. The detection limit was determined to be 1.22 $\mu\text{g/kg}$, and its limit of quantitation (LOQ) was found to be 4.07 $\mu\text{g/kg}$, showing very good results (Zhang et al., 2023b).

Various recent methods of pesticide detection using nanoparticles, especially noble metal nanoparticles. Gold nanoparticles (AuNPs), for example, exhibit extraordinary colors due to the localized surface plasmon resonance termed (LSPR), which is a phenomenon whereby the surface electrons of noble metal nanoparticles fluctuate at the same frequency when light interacts with them, leading to an increase in electromagnetic fields on the particles surface that affects Surface Enhanced Raman Scattering (SERS) as well as Surface Enhanced Fluorescence (SEF) (Cho et al., 2012). The Van der Waal attraction between the particles and the charge on the particles are intimately related to the colloid stability of nanoparticles; however, these forces may be disrupted by salt ions and coordination bond interactions. This causes a change in color because of the aggregated nanoparticles.

A colorimetric detection apparatus using AuNPs takes advantage of the fact that binding pesticides like methyl parathion to them induces a noticeable switch from red to blue. This technique can detect even trace amounts of pesticides at low concentrations with extremely high specificity and sensitivity. Besides, aptamer-based sensors using AuNPs can detect pesticides like acetamiprid through aptamer-induced nanoparticle aggregation, thus offering a quick, cheap, and easy method for analyzing plant samples containing pesticide residues. Such advances underscore the prospects for colorimetric detection using nanoparticle systems (Dissanayake et al., 2019; Qi et al., 2020). Because SERS provides the molecular structure's "fingerprint" at low concentrations, it becomes a highly selective and ultra-sensitive pesticides detection method (Lin et al., 2018). Pham et al. (2019) utilize SERS optical fiber substrates to give a well-known monitoring method for permethrin pesticide detection. An Ag nano-dendrite optical fiber substrate was employed to identify permethrin insecticide in the concentration range of (0.1–20 ppm). Consequently, they argue that such a substrate could find applications in pesticide detection, food safety, and environmental monitoring. Also, nanocomposites including magnetic and graphene nanocomposites are used to selectively detect, remove and break down pesticides (Patle et al., 2020).

3.3.2.2 Biosensors

Bahadır and Sezgintürk (2015) describe biosensors as analytical tools that can perform a number of different functions in numerous scientific fields. They have gradually transformed from wearable and implantable biosensors to conventional electrochemical ones. Nowadays, these devices are employed in numerous fields, including biosecurity, environmental monitoring, and food safety. Biosensors for identifying pesticide residues are quick, accurate, economical, specific, and super sensitive. In addition, developed biosensors are useful for in situ pesticide analysis at trace levels and are reusable. Different biosensors have been created and used efficiently for detecting pesticides, including enzymatic, whole-cell, immunosensors, and DNA-based biosensors. Nanomaterial-based biosensors show great sensitivity and stability for pesticide detection on-site (Vohra et al., 2020; Parihar et al., 2024). Nanobiosensors are composed of substances that have small sizes and act as bioreceptors on a transducer that provided a signal for identifying elements in order for checking the single or multiple analytes (Arduini et al., 2016). Even if the applications for nanomaterials-based sensing for pesticide residue identification are vast, there are still several aspects to consider, including the cost of the sensors, reusable sensors' ability for pesticide detection, the simplicity of sensor fabrication techniques and instrumentation, The need for repeatability and dependability in trace level detection, and problems with nanomaterial exposure to the environment (Viswanathan & Manisankar, 2015).

Biosensing techniques for detecting organophosphate pesticides can be divided into catalytic methods and affinity-based methods, depending on the type of recognition element used. The use of enzymes in the catalytic detection of organic pollutants

offers a wide range of options. Due to enzyme's binding with organophosphates, research has been conducted to evaluate them as potential candidates for detecting organophosphates pesticides. These enzymes include acetylcholinesterases (AChE), lipase, tyrosinase, esterase, and organophosphorous hydrolase (Liu et al., 2022a, b). Most of the organophosphate biosensors today depend on AChE enzyme activity inhibition as an indirect way to detect them. Chaudhari et al. (2023) designed an acetylcholinesterase binding-based biosensor for highly accurate organophosphate pesticide detection. This biosensor is appropriate for field applications, enabling quick and dependable detection of pesticide residues while requiring a minimum of sample preparation. Thus, it becomes an indispensable tool for site monitoring in agricultural and environmental areas.

Regarding nanobiocatalysts, they were developed by merging biotechnology and nanotechnology based on the application of nanotechnology and the possibility for enzyme immobilization onto nanomaterials. Food pollutant elements can be identified, such as microbial cells or their metabolic products, heavy metals, antibiotics, and other pesticide residues using nanobiocatalysts. These have yielded success due to their high detection precision (Mohammadi et al., 2023).

An innovative electrochemical sensor was created for the identification of carbendazim. The hydrothermal method was employed to produce iron oxyhydroxide nanoparticles, and after that molecularly imprinted polymer was electropolymerized on it, using carbendazim as a template and resorcinol as a functional monomer. The high selectivity and sensitivity of the MIP/ β -FeOOH/CC-based electrochemical sensor originate from the collaboration between β -FeOOH and MIP, thus making it an efficient means to detect pesticide residue levels (Yang et al., 2024).

Although nanomaterials employed in biosensors demonstrate remarkable sensitivity and specificity features, environmental concerns about them hover above like a dark cloud. There is a need for assessment before the release of nanoparticles to ecosystems and food chains so that their safety and sustainable use will be guaranteed. This incorporates evaluating potential long-term health effects on humans and non-target organisms, then formulating rules for using them in food safety checking and environmental observing (Ghareeb et al., 2022, 2023).

Artificial Intelligence in Biosensor

Biosensors and artificial intelligence have made great strides in advancing together. A few different sensors that work at once in a smartphone is the best example of a sensor platform that is very well-integrated (BalaKrisna et al., 2023). Li et al. (2024) presented an effortless and affordable strategy employing PtCu₃ alloy nanocrystals, which possess peroxidase-like properties for colorimetric detection of organophosphorus pesticides. Using a smartphone, pesticide concentrations in fruit peelings can simply be determined by contrasting the outcomes on colorimetric test strips with those of the calibration curve. Liu et al. (2023) created portable and cost-effective pesticide detectors by merging colorimetric biosensors with deep learning systems

for smartphones. For quick and reliable identification of permethrin, a distinctive colorimetric detector based on metronidazole-stabilized silver nanoparticles (MTZ-AgNPs) has been developed, and a limit of detection is $0.0104 \mu\text{M}$. This sensor is based on microfluidic paper-based analytical devices (μPADs) and modern smartphones and allows on-site analysis and remains relatively selective. The UPLC technique was used on apple and tomato extracts to verify the accuracy of permethrin using quantitative analytical methods (Rasheed et al., 2023). Zhao et al. (2020) created an intelligent wearable biosensor for the detection of organophosphate pesticides on the surface of plants. This system can select and identify methyl parathion, and the findings are transmitted to the smartphone, making it possible for real-time electrochemical examination of pesticides on surfaces of agricultural products. On the surface of three-dimensional porous laser-induced graphene, AuNPs were used to improve electrochemical performance. Guo et al. (2015) present an assay that measures levels of methyl parathion via smartphone-readable barcode. Acetylcholinesterase activity is inhibited by methyl parathion, which causes a color change in response to its concentrations. A PDMS channel plate under a printed barcode is used as the reaction reservoir. Thus, the barcode can be scanned by an app on a smartphone after which it shows whether the pesticide exists. Therefore, this portable and easy-to-use method can be an alternative to spectrophotometric methods.

3.4 Nanotechnology Approaches for Removal and Degradation of Pesticides

Several traditional approaches have been reported for pesticide breakdown and removal. Mostly biological, chemical, physical, and thermal methods were used for the removal and minimization of pesticides and their degraded products from the environment. Figure 3.5 represents various traditional and nanotechnology-based approaches applied for pesticide removal and degradation.

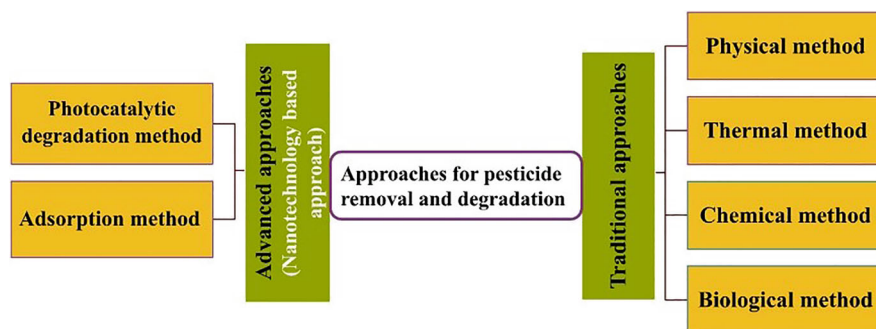


Fig. 3.5 Traditional and nanotechnology-based approaches applied for pesticides removal and degradation

The breakdown of many pesticides is difficult by the traditional degradation techniques. These pesticides persist in the soil and groundwater, and harm the environment in their wake. Furthermore, their chemical properties allow them to infiltrate living systems and accumulate within food chains (Sharma et al., 2019). Therefore, efforts and extensive research focus on identifying or developing efficient, cost-effective, and eco-friendly methods for degrading them at rapid and high rates into non-toxic forms to decrease their effect on the environment and humans. Since the introduction of more advanced technology in recent years, the potential health risks posed by pesticides have reached a molecular level, meaning that a small number of these agrochemicals would be sufficient to have a negative effect on human health. The field of nanotechnology is one that can achieve this idea. Recently, approaches based on nanotechnology have attracted worldwide interest for the purpose of breaking down and eliminating dangerous pesticides. It is well known that these approaches are quite specific in pesticide degradation (Tripathy et al., 2024). Moreover, with the use of nanomaterials in illness therapy, the effectiveness of drugs is improved, and there are no toxic effects on normal human cells (Taher et al., 2017; El-Didamony et al., 2022).

Over the past few years, these unique characteristics have enabled various nanoparticles to be used for the detection, breakdown, and elimination of different pesticides (Rawtani et al., 2018). The most effective removal methods of pesticides are adsorption and photocatalytic degradation. Various studies have demonstrated that nanomaterials such as nanotubes, nanoparticles, and nanocomposites have exhibited promising results in the removal and degradation of pollutants, including persisting organic compounds and heavy metals (Farooq et al., 2023). They are considered important nano-adsorbents and photocatalysts. They may be distinguished from the corresponding bulk material (Bibi et al., 2021; Selmani et al., 2022).

The main backbone of nanotechnology-based approach is photocatalysis that basically requires high-tech oxidative activity in presence of photo energy resulting in mineralization of organic pollutants (Bai et al., 2017). Also, the adsorption approach has gained popularity because of its ease of use, flexibility, insensitivity, and effectiveness.

3.4.1 Photocatalytic Degradation Technique

Photocatalysis is a sustainable method for getting rid of a variety of organic contaminants. It is an appropriate pretreatment for dangerous and non-biodegradable contaminants to increase their biodegradability. Moreover, photocatalysis can serve as a polishing step for treating recalcitrant organic substances (Taghizade Firozjaee et al., 2018). Several nanomaterials including metals nanoparticles such as silver or metal oxides nanoparticles such as ZnO and TiO₂ are very good photocatalysts with unique features and seem to be the newest revolutionary technology for destruction (Table 3.3). It also does not require mass transfer and can even be done under surrounding conditions; oxygen in the air is used for oxidation (Rani & Shanker, 2018).

Table 3.3 Different nanomaterials used as photocatalysts for pesticides photodegradation

Photocatalysts	Type of nanomaterial	Target pesticide	Matrix	Light source	Degradation efficiency (%)	Reference
CuO	Metal oxide NPs	Lambda-cyhalothrin	Water	UV	99	Iqbal et al. (2021)
NiO	Metal oxide NPs	Lambda-cyhalothrin	Water	UV	(~89%)	Iqbal et al. (2021)
Co3O4/MCM-41	Carbon nanospheres	Methyl parathion	Water	Visible	100	Adeola et al. (2022)
CuO/TiO2/PANI	Metal oxide/metal oxide NCs	Chlorpyrifos	Water	Visible	95	Nekooie et al. (2021)
Ag@TiO2	Metal/metal oxide NCs	4-Chlorophenol	Wastewater	Solar	91.3%	Huong et al. (2024)
Cu-Zn	Bimetallic NPs	Monocrotophos, chlorpyrifos, cypermethrin and carbendazim	Water	Visible	53–95%	Singh and Devi (2024)
Fe-CDs/MOF-808	Fe/carbon dots (Fe-CDs) with metal-organic framework	Paraoxon and parathion	Pak choi food	Visible	100%	Ma et al. (2023)
CQDs-SH/CdS QDs	0-dimensional carbon quantum dots	Imidacloprid	Water	Visible	90.13	Targhan et al. (2024)
La-ZnO-PAN fibers	Metal oxide/polymers NCs	Atrazine	Aqueous solution	UV	98	Krishnasamy et al. (2022)
ZnO	Metal oxide NPs	Monocrotophos	Aqueous solution	UV	88	Bharti et al. (2021)
rGO/ZnO	2-dimensional (2D) carbon NMs (graphene oxide)	Metalaxyl	Aqueous solution	UV	90.25	Dehghan et al. (2022)
ZnO	Metal oxide NPs	Temephos	Water	Sunlight	100	Serrano-Lázaro et al. (2020)
ZnO/TiO2-Fe3O4	Metal oxide/metal oxide NCs	Chlorpyrifos	Aqueous solution	Visible	94.8	Saljooghi et al. (2021)
Cu-ZnO	Metal/metal oxide NCs	Chlorpyrifos	Wastewater	Sunlight	91	Pathania et al. (2021)
ZnO/CuO	Metal oxide/metal oxide NCs	Triclopyr	Aqueous solution	UV	100	Kumari et al. (2021)

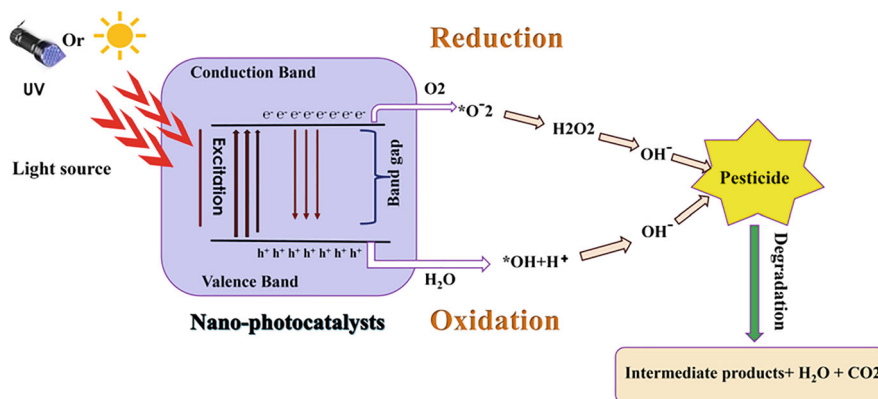


Fig. 3.6 Schematic diagram illustrating the photocatalytic degradation mechanism of nanomaterials

The Mechanism of Photocatalytic Degradation

When nanomaterials are exposed to light sources such as UV, visible light, and solar energy they are excited as semiconductors. Then, create electron (e^-)– hole (h^+) combinations that go toward the semiconductor surface. The semiconductor region displays fast excitation at lower energies within the range of nanoparticles. The electron-hole pairs interact with molecular oxygen and hydroxide ions, giving rise to free radicals like reactive oxygen species and superoxide radicals, which cause photodegradation. Finally, organic pesticides are degraded into non-toxic products through photooxidation (H_2O_2 conversion to OH) or photoreduction (O_2 conversion to O_2^- and OH). The rate of break down can be increased by reducing the catalyst particle size or doping with other photocatalysts or nitrogen. In these processes, the gap in energy levels of the material is manipulated, which will allow for easier photooxidation or photoreduction. (Rani & Shanker, 2018). The photocatalytic degradation mechanism of nanomaterials has been reported in previous studies (Lavand & Malghe, 2015; Tripathy et al., 2024). The basic mechanism of photocatalysis is represented in Fig. 3.6.

3.4.2 Adsorption Technique

Adsorption is a separation process where molecules of fluid, liquid, or gas attach themselves to the outside and inside surfaces of a solid substance known as the adsorbent. The term “adsorbent” refers to the substance that supplies the surface. Adsorbates are the pollutants that are present in either the liquid or gaseous phase. Selective adsorption (thermodynamic and kinetic selectivity) from the adsorbate is

the basis for separation because of mass transfer and particular interactions between the surfaces of adsorbents and polluting substances (Saleh, 2022). The adsorbent and the adsorbate react with each other in two ways: chemisorption and physisorption. An irreversible chemical reaction between them that is controlled by chemical bonds is known as Chemisorption. Conversely, the more prevalent process of physisorption is reversible and governed by London force, dipole-dipole attraction, Van der Waal's bonds, and other factors (Crini et al., 2018). The adsorption process depends on different factors that must be adjusted such as temperature, pH, time, sorbent dosage and pesticide concentration. The adsorption capacity can be calculated from the following equation:

$$Q_{max} = C_0 - C_e \cdot m \times V$$

where C_0 is the pesticide's initial concentration (mg/L), C_e is its equilibrium concentration (mg/L), m is the adsorbent's mass (g), and V is the solution's volume (L).

For a number of micropollutants, nano-adsorbents can provide ultrahigh adsorption capacities, high adsorption efficiency, quick adsorption kinetics, and selectivity (Shanaah et al., 2023). Table 3.4 displays different nanoadsorbents used for the removal of numerous pesticides.

3.5 Nano-adsorbents and Photocatalysts Characteristics

In recent years, nanomaterials have been used to remove and degrade pesticides, categorized into nanoparticles, nanocomposites, and carbon-based nanomaterials. This classification of nanomaterials further divides into many subclasses. Different classes of nanomaterials used for elimination and breakdown of pesticides are represented in Fig. 3.7. Researchers have utilized the major NPs categories, including metal oxide NPs, metal NPs, and bimetallic NPs, to identify and eliminate pesticides (Rawtani et al., 2018). However, it is necessary now to develop the structural characteristics of photocatalysts and nano-adsorbents. To obtain the prolonged recombination of the charge carriers and improve photo-degradation, many methodologies have been used to provide improved performance in chemisorption, physisorption, and band gap reduction of the photocatalysts (Farooq et al., 2020).

The main methods utilized to modify the properties of nano-adsorbents and photocatalysts are doping these materials with different metals, multi-functionalizing the surface, through the development of nanocomposites such as metal/metal oxides, metal oxides/metal oxides, and metal oxides/polymers (Shanaah et al., 2023).

Table 3.4 Different nanomaterials are used as adsorbents for pesticides removal

Nanomaterial adsorbent	Type of nanomaterial	Target pesticides	Matrix	Removal efficiency (%)	Reference
CeO ₂	Metal oxide NPs	Parathion methyl	Water	90.6%	Tolasz et al. (2020)
CeO ₂	Metal oxide NPs	2,4-Dichlorophenoxyacetic acid	Water	95.78%	Elhussein et al. (2018)
Fe ₃ O ₄ /CuO@AC	Metal oxide/metal oxide/carbon	Imidacloprid	Water	99.6%	Parsaie et al. (2024)
Chitosan–CuO	Metal oxide/polymers NCs	Fenamiphos & diazinon	Water	99.36% & 89.04%	Badawy et al. (2018)
Chitosan-ZnO	Metal oxide/polymers NCs	Lambda-cyhalothrin	Water	99.09%	Badawy et al. (2018)
N-NiO@N-Fe ₃ O ₄ @N/ZnO	Metal/metal oxide NCs	Atrazine	Wastewater	92%	Allam et al. (2021)
MOM-Fe ₃ O ₄	Metal oxide/carbon based NMs	Triclosan	Wastewater	96.48	Cusioli et al. (2021)
MgAl ₂ O ₄	Metal/metal oxide NCs	Dimethomorph	Water	90–94%	Rao et al. (2020)
ZnO-CP	Metal oxide/carbon based NMs	Metribuzin	Water	200 mg/g	Haq et al. (2022)
MWCNTs	Carbon based	Cypermethrin, chlorpyrifos	Tea samples	70%	Hou et al. (2014)

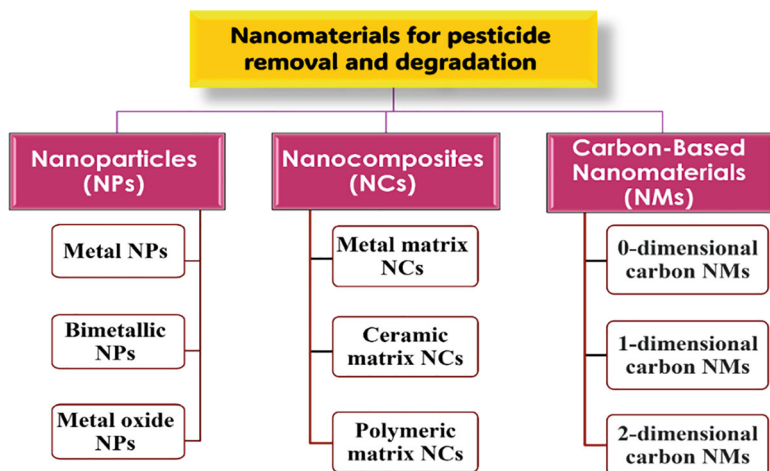


Fig. 3.7 Classification of nanomaterials used for pesticide removal and degradation

3.5.1 Nanoparticles (NPs)

3.5.1.1 Metal Nanoparticles

Nanoparticles made from just a single element are known as metal nanoparticles. Among the most often produced metal nanoparticles are Au, Ag, Cu, Zn, Fe, Al, Cd, Co and Ni. Their broad electromagnetic spectrum absorption, strong reactivity, and localized surface plasmon resonance (LSPR) are among their noteworthy qualities. Because of their enhanced catalytic, optical, antimicrobial/cancer/viral, optoelectrical, and other properties, metal nanoparticles are highly attractive materials for a wide range of practical applications (Chakraborty & Pradeep, 2017). Biosynthesized iron nanoparticles (Fe NPs) have been utilized for the elimination of 2,4 dichlorophenol by adsorption approach. Fe-NPs serve as the heterogeneous catalyst. Acetone and acetic acid, the first degradation products to develop because of the pesticide's benzene ring opening during degradation, were identified using GC-MS (Guo et al., 2017). Synthesis of silver (Ag) nanoparticles through ultrasonic hydrodistillation extraction method from *Cymbopogon nardus* plant was done by (Kamarudin et al., 2019) for degradation of 2,4-Dichlorophenoxyacetic acid herbicide. The synthesized Ag nanoparticle in spherical shape with size ranging between 10 and 50 nm displayed higher degradation percentages toward the 2,4-dichlorophenoxyacetic acid (98%).

3.5.1.2 Bimetallic Nanoparticles

Bimetallic NPs consist of atoms from two different metals combined within a single nanoparticle. The synergistic effects of mixing the metals lead to the development of

novel properties in bimetallic nanoparticles (Zaleska-Medynska et al., 2016). Hence, the synthesis of bimetallic NPs such as Fe/Ni, Ag/Cu and Cu–Zn NPs received greater interest than that of monometallic nanoparticles. Bimetallic Fe/Ni NPs have been used as effective catalysts for the breakdown of profenofos. The insecticide was broken down by nanoscale zero valent iron (nZVI) particles acting as a reducing agent. Fe/Ni bimetallic NPs at 13.83 g/L concentration and pH 5.12 achieved (94.51%) removal percent of profenofos at 1.4 mg/L concentration (Mansouriieh et al., 2019). Chlorpyrifos in water has been degraded by green synthesized Ag/Cu bimetallic NPs. Ag/Cu bimetallic NPs can be helped to provide an environmentally friendly way and employed for cleaning water from pesticide pollution (Rosbero & Camacho, 2017). Moreover, green calcined bimetallic Fe/Pd nanoparticles (Calcined-Fe/Pd NPs) were synthesized by (Lin et al., 2021) through the extraction of *eucalyptus* leaf to remove arsenic from wastewater. The specific surface area increased because of calcination, providing more active adsorption sites for arsenite and arsenate. Under ideal experiment conditions, calcined-Fe/Pd NPs eliminated arsenite from wastewater with 100% removal efficiency.

Interestingly, Singh and Devi (2024) synthesized Cu–Zn bimetallic nanostructures utilizing Zinger extract for the photo-catalytic degradation of different pesticides, specifically carbendazim, chlorpyrifos, monocrotophos, and cypermethrin. Based on UV-VIS spectroscopy, the Cu–Zn bimetallic nanoparticles degraded (53–95%) of these pesticides in 24–72 h of incubation.

3.5.1.3 Metal Oxide Nanoparticles

Metal oxide nanoparticles (NPs) have found extensive application in environmental cleaning up, generally because of their conducting characteristics. Also, because of their great adsorption ability, they have been employed in several studies for elimination of pesticide. Different metal oxide nanoparticles such as zinc oxides, magnesium oxides, ferric oxides, cobalt oxides, titanium oxides, copper oxides cerium oxide, aluminum oxides, among others have displayed proficient elimination and breakdown outcomes to contaminants such as persistent organic chemicals and heavy metals (Farooq et al., 2023). Phuinthiang and Kajitvichyanukul (2019) synthesized The TiO₂ nanoparticles from *Coffea arabica* L. extract (TiO₂/C) for the elimination of paraquat pesticide from contaminated water through photocatalytic process. Due to paraquat's capacity to adsorb on the surface of TiO₂/C, it is effectively eliminated in alkaline media. The most effective process is the combination of TiO₂/C with UV and H₂O₂ that exhibits 66.3% degradation of paraquat (50 mg/L) at pH 10 and 90 min. Metal oxide nanoparticles are good destructive absorbents for organophosphorus pesticides; however, producing them in high quality presents challenges and difficulties because of the associated expenses (Taghizade Firozjaee et al., 2018). In the same way, degradation of the organophosphorus pesticide parathion methyl was achieved by nanocrystalline cerium (IV) oxide prepared under favorable temperature. Parathion methyl degradation resulted in the formation of less toxic products 4-nitrophenol (4-NP) (Tolasz et al., 2020).

Biosynthesis of CuO and NiO nanocatalysts with large-surface-area for removal of Lambda-cyhalothrin pesticide from contamination water was made by (Iqbal et al., 2021). CuO photocatalyst has more degradation efficiency than NiO photocatalyst. The Lambda-cyhalothrin degradation percentages were (~99%) and (~89%) for CuO and NiO nanoparticles, respectively. The photocatalytic degradation of trace element Arsenic (Cd & Se) and monocrotophos Organophosphorus pesticide was reported in the study of (Bharti et al., 2021) using ZnO NPs with less than 100 nm size under UV reactor. It was shown that monocrotophos degradation records 88% at a pH 4 and 2 g of nanocatalyst for 120 min. However, the removal of Cd and Se were 36% and 64%, respectively at the same conditions.

3.5.2 Nanocomposites (NCs)

A nanocomposite is a combination of several materials with nanoscale dimensions. Generally, nanocomposites are composed of two or more distinct components or phases separated by a distinct interface. The component that is found in larger amounts is called matrix, while reinforcement is a component that is incorporated into matrix to enhance the mechanical characteristics of nanocomposites (Khan et al., 2016).

Recently, nanocomposites received greater attention than nanoparticles because when comparing conventional nanoparticles to nanocomposites, it is shown that nanocomposites have a higher surface to volume ratio and a larger surface area (Rawtani et al., 2018).

The nanocomposites are classified into three classes based on the type of matrix and reinforcement materials used in their structure. These types are Metal matrix nanocomposites (e.g. NiO/ZnO/Ag, Fe/MgO), ceramic matrix nanocomposites (e.g. Al₂O₃/TiO₂, SiO₂/Ni), and Polymer matrix nanocomposites (e.g. polyester/TiO₂) (Lateef & Nazir, 2017).

3.5.2.1 Metal Matrix and Ceramic Nanocomposites

Although numerous metal oxides such as TiO₂, ZnO, and Bi₂O₃ have distinct physicochemical characteristics such as high sensitivity, area of surface, and strong stability. These metal oxides need exposure to UV sources to be excited due to their high band gap. This issue reduces their potential as materials in sunlight (Rani & Shanker, 2018). The doping of some metals, metal oxide or other semiconductors with nanomaterials may overcome these restrictions such as surface defects, band gap alteration, and high recombination efficiency of photogenerated (e⁻/h⁺) for effective application in environmental remediation (Rani et al., 2022). Many research works have utilized these modified nanomaterials for degradation of pesticides. Photocatalytic degradation of aqueous dichlorvos was investigated by Siva Rao et al. (2012) who synthesized TiO₂ and doped with magnesium (Mg²⁺-TiO₂). Compared with the undoped counterpart, the doped catalyst had a larger surface area

and smaller particle size. Catalytic activity was found to be in Mg^{2+} - TiO_2 doped catalysts better than undoped TiO_2 .

In a similar attitude, the highly toxic glyphosate organophosphorus herbicide has been removed from water by photocatalytic degradation using magnetic $\text{BiOBr}/\text{Fe}_3\text{O}_4$ nanocomposites prepared by Cao et al. (2019). Also, photocatalytic degradation of Lambda-Cyhalothrin using $\text{ZnO}-\text{Bi}_2\text{O}_3$ at visible light was more effective than that compared to bare ZnO and achieved 85.7% degradation percentage at 50 mg/L of pesticide and 120 minutes (Premalatha & Miranda, 2019). In a very recent study of Huong et al. (2024), 4-chlorophenol (4CP) pesticide which considered a substantial hazard effect on both the ecosystem and human health was degraded by Ag-doped TiO_2 (Ag@TiO_2). It has shown significant efficiencies of 91.3% and 72.8% in removing 4CP under both visible and solar light, respectively. Also, it shows outstanding photodegradation efficiency for 4CP (98.8%) at concentration of (1 mg/L). Moreover, Ag@TiO_2 exhibited substantially higher removal for 4CP (81.6%) compared to TiO_2 (27.6%) in wastewater.

3.5.2.2 Polymers Matrix Nanocomposites

Composites made of polymers are the most environmentally friendly and exhibit the best-performing values. Natural biodegradable polymers are appropriate for the matrix materials in nanocomposites. Examples of these include polysaccharides, proteins, and lipids. (Dufresne, 2012). A cross-linked chitosan-silver nanoparticle composite was synthesized by (Saifuddin et al., 2011) for elimination of atrazine pesticides from water. Silver nanoparticles was embedded in biodegradable and non-toxic natural polymer chitosan using microwave irradiation. A column of cross-linked chitosan-silver nanoparticle composite micro-beads was employed in an on-line filter to carry out the long-term removal of pesticides. Dehaghi et al. (2014) Synthesized chitosan- ZnO nanoparticles ($\text{CS}-\text{ZnONPs}$) composite beads using a polymer-based method. The 0.5 g of the $\text{CS}-\text{ZnONPs}$ eliminated 99% of the permethrin pesticide solution (0.1 mg/L, 25 mL) at ambient temperature and pH (7). Moreover, through nano-clay minerals, various pesticides like cypermethrin, atrazine, metribuzin, chlorpyrifos, β -endosulfan, pendimethalin, α -endosulfan, aldrin, DDT, and lindane could be removed from water (Shabeer et al., 2015).

3.5.3 Carbon-Based Nanomaterials (CBNs)

Due to their distinct physical and chemical properties, carbon-based nanomaterials have demonstrated a lot of promises for a variety of environmental applications. Structures and morphologies of CBMs can be specifically manipulated due to their special hybridization properties (Mohapatra et al., 2023). Carbon nanomaterials were classified based on their dimension features into three categories: (1) Zero-dimensional (0-D) carbon, such as fullerene, graphene quantum dots, and carbon dots; (2) 1-dimensional (1D) carbon, for example, carbon nanofiber and carbon

nanotubes; (3) 2-dimensional (2D) carbon, as in graphene, graphitic carbon nitride, and grapevines (Devi et al., 2023). The usage of multi-walled carbon nanotubes (MWCNTs) as nano-adsorbent for the elimination of 78 pesticide residues from tea was investigated by (Hou et al., 2014). Most actual tea samples indicated the presence of atrazine, chlorpyrifos, pyridaben, cypermethrin, buprofezin, and diazinon. MWCNTs have demonstrated great potential as a nanomaterial with high elimination efficiency. Moreover, the ability of synthetic multi-walled carbon nanotubes (MWCNTs) to remove organophosphorus malathion insecticide from water by an adsorption technique was investigated by Dehghani et al. (2017). Maximum elimination (100%) of malathion was obtained. Some researchers utilized graphene and modified graphene oxide bonded with other materials for removal of persistent pesticides. To improve the efficiency of graphene as sorbent, Graphene-coated silica (GCS) was prepared and applied for organophosphates removal from water (Taghizade Firozjaee et al., 2018).

Another carbon-based nanomaterial is graphitic carbon nitride ($g\text{-C}_3\text{N}_4$). It has shown great promise as a semiconductor and is especially remarkable for its possible use as a photocatalyst. Truc et al. (2019) developed a photocatalyst system $\text{Cu-ZnO/g-C}_3\text{N}_4$ for efficient atrazine breakdown. Carbon quantum dots (CDs) are a new class of carbon nanomaterials. It showed great potential as semiconductors in removal of pesticides because of their low toxicity, biocompatibility, and optical properties (Lim et al., 2015). For the sensitive and selective degradation of paraoxon and parathion, Ma et al. (2023) created nanoreactors consisting of metal-organic frameworks (MOF-808) and iron-doped carbon dots (Fe-CDs). They reported that it can break down organophosphates in Pakchoi within 5 min. In a new strategy by (Targhan et al., 2024), they synthesized carbon quantum dots containing many thiol groups (CQDs-SH) as a passivating vehicle for the maintenance of CdS quantum dots for photocatalytic degradation of imidacloprid insecticide. The synthesized CQDs-SH/CdS QDs nanomaterial effectively degraded the imidacloprid insecticide from an aqueous solution with (90.13% degradation) under visible light at pH 9 and 90 min.

3.6 Conclusion

Nanomaterials are considered powerful tools in detecting, eliminating, and breaking down pesticides, providing solutions to the limitations of traditional methods. Their distinctive properties make them efficient at detecting and removing pesticide residues. They provide quickness, sensitivity, and selectivity for detecting pesticides, which is critical for an instant response and minimizing human exposure to hazardous substances. Besides, nanomaterials have indicated a lot of potential in breaking down pesticides into harmless substances, thus lowering their environmental impact. The engineered nanomaterials help for targeted degradation processes that are efficient and eco-friendly compared to traditional ones. In summary, pesticide detection and degradation will greatly benefit from ongoing research using nanomaterials with the goal of a safer and more sustainable environment.

References

- Adeola, A. O., Abiodun, B. A., Adenuga, D. O., & Nomngongo, P. N. (2022). Adsorptive and photocatalytic remediation of hazardous organic chemical pollutants in aqueous medium: A review. *Journal of Contaminant Hydrology*, 248, 104019.
- Allam, E. A., Ali, A. S., Elsharkawy, R. M., & Mahmoud, M. E. (2021). Framework of nano metal oxides N-NiO@ N-Fe₃O₄@ N-ZnO for adsorptive removal of atrazine and bisphenol-A from wastewater: Kinetic and adsorption studies. *Environmental Nanotechnology, Monitoring & Management*, 16, 100481.
- Arduini, F., Neagu, D., Scognamiglio, V., Patarino, S., Moscone, D., & Palleschi, G. (2015). Automatable flow system for paraoxon detection with an embedded screen-printed electrode tailored with butyrylcholinesterase and prussian blue nanoparticles. *Chem*, 3(2), 129–145.
- Arduini, F., Cinti, S., Scognamiglio, V., & Moscone, D. (2016). Nanomaterials in electrochemical biosensors for pesticide detection: Advances and challenges in food analysis. *Microchimica Acta*, 183, 2063–2083.
- Badawy, M. E., El-Nouby, M. A., & Marei, A. E. S. M. (2018). Development of a Solid-Phase Extraction (SPE) Cartridge Based on Chitosan-Metal Oxide Nanoparticles (Ch-MO NPs) for extraction of pesticides from water and determination by HPLC. *International Journal of Analytical Chemistry*, 2018(1), 3640691.
- Bahadır, E. B., & Sezgentürk, M. K. (2015). Applications of commercial biosensors in clinical, food, environmental, and bioterror/bio warfare analyses. *Analytical Biochemistry*, 478, 107–120.
- Bai, H., Zhou, J., Zhang, H., & Tang, G. (2017). Enhanced adsorbability and photocatalytic activity of TiO₂-graphene composite for polycyclic aromatic hydrocarbons removal in aqueous phase. *Colloids and Surfaces B: Biointerfaces*, 150, 68–77.
- BalaKrisna, G., Shaikh, A. H. A. M., Tiwari, M., & Deepa, K. (2023). Artificial intelligence and nanotechnology in biosensors. In *Handbook of research on advanced functional materials for orthopedic applications* (pp. 47–64). IGI Global.
- Bever, C. R., Majkova, Z., Radhakrishnan, R., Suni, I., McCoy, M., Wang, Y., et al. (2014). Development and utilization of camelid VHH antibodies from alpaca for 2, 2', 4, 4'-tetrabrominated diphenyl ether detection. *Analytical Chemistry*, 86(15), 7875–7882.
- Bharti, Jangwan, J. S., Kumar, G., Kumar, V., & Kumar, A. (2021). Abatement of organic and inorganic pollutants from drinking water by using commercial and laboratory-synthesized zinc oxide nanoparticles. *SN Applied Sciences*, 3(3), 311.
- Bian, H., Yao, H., Lin, G., Yu, Y., Chen, R., Wang, X., et al. (2020). Multiple kinds of pesticides detection based on back-propagation neural network analysis of fluorescence spectra. *IEEE Photonics Journal*, 12(2), 1–9.
- Bibi, S., Ahmad, A., Anjum, M. A. R., Haleem, A., Siddiq, M., Shah, S. S., & Al Kahtani, A. (2021). Photocatalytic degradation of malachite green and methylene blue over reduced graphene oxide (rGO) based metal oxides (rGO-Fe₃O₄/TiO₂) nanocomposite under UV-visible light irradiation. *Journal of Environmental Chemical Engineering*, 9(4), 105580.
- Botta, R., Eiamchai, P., Horprathum, M., Limwichean, S., Chananonwathorn, C., Patthanasettakul, V., et al. (2020). 3D structured laser engravings decorated with gold nanoparticle SERS chips for paraquat herbicide detection in environments. *Sensors and Actuators B: Chemical*, 304, 127327.
- Bratovic, A., Hikal, W. M., Mehdizadeh, M., Al Ahl, H. A., Omid, A., Adetunji, C. O., et al. (2023). Application of nanotechnology in agroecosystems: Nanoparticles for improving agricultural production. *Reviews in Agricultural Science*, 11, 291–309.
- Cao, L., Ma, D., Zhou, Z., Xu, C., Cao, C., Zhao, P., & Huang, Q. (2019). Efficient photocatalytic degradation of herbicide glyphosate in water by magnetically separable and recyclable BiOBr/Fe₃O₄ nanocomposites under visible light irradiation. *Chemical Engineering Journal*, 368, 212–222.

- Chakraborty, I., & Pradeep, T. (2017). Atomically precise clusters of noble metals: Emerging link between atoms and nanoparticles. *Chemical Reviews*, 117(12), 8208–8271.
- Chaudhari, P., Chau, L. K., Ngo, L. T., Chang, T. C., Chen, Y. L., & Huang, K. T. (2023). Competitive assay for the ultrasensitive detection of organophosphate pesticides based on a fiber-optic particle plasmon resonance biosensor and an acetylcholinesterase binding peptide. *Analytical Chemistry*, 95(39), 14600–14607.
- Cheng, N., Shi, Q., Zhu, C., Li, S., Lin, Y., & Du, D. (2019). Pt–Ni (OH) 2 nanosheets amplified two-way lateral flow immunoassays with smartphone readout for quantification of pesticides. *Biosensors and Bioelectronics*, 142, 111498.
- Cho, W. J., Kim, Y., & Kim, J. K. (2012). Ultrahigh-density array of silver nanoclusters for SERS substrate with high sensitivity and excellent reproducibility. *ACS Nano*, 6(1), 249–255.
- Crini, G., Lichtfouse, E., Wilson, L. D., & Morin-Crini, N. (2018). Adsorption-oriented processes using conventional and non-conventional adsorbents for wastewater treatment. In *Green adsorbents for pollutant removal: Fundamentals and design* (pp. 23–71). Springer.
- Cusioli, L. F., Quesada, H. B., de Andrade, M. B., Gomes, R. G., & Bergamasco, R. (2021). Application of a novel low-cost adsorbent functioned with iron oxide nanoparticles for the removal of triclosan present in contaminated water. *Microporous and Mesoporous Materials*, 325, 111328.
- Dehaghi, S. M., Rahmanifar, B., Moradi, A. M., & Azar, P. A. (2014). Removal of Fpermethrin pesticide from water by chitosan–zinc oxide nanoparticles composite as an adsorbent. *Journal of Saudi Chemical Society*, 18(4), 348–355.
- Dehghan, S., Tahergorabi, M., Norzaee, S., Boorboor Azimi, E., Hasham Firooz, M., & Dadban Shahamat, Y. (2022). Preparation and photocatalytic performance of reduced graphene oxide/ZnO nanocatalyst for degradation of metalaxyl from aqueous solution: Effect of operational parameters, mineralisation and toxicity bioassay. *International Journal of Environmental Analytical Chemistry*, 102(18), 7112–7134.
- Dehghani, M. H., Niasar, Z. S., Mehrnia, M. R., Shayeghi, M., Al-Ghouti, M. A., Heibati, B., et al. (2017). Optimizing the removal of organophosphorus pesticide malathion from water using multi-walled carbon nanotubes. *Chemical Engineering Journal*, 310, 22–32.
- Devi, M. K., Yaashikaa, P. R., Kumar, P. S., Manikandan, S., Oviyapriya, M., Varshika, V., & Rangasamy, G. (2023). Recent advances in carbon-based nanomaterials for the treatment of toxic inorganic pollutants in wastewater. *New Journal of Chemistry*, 47(16), 7655–7667.
- Dissanayake, N. M., Arachchilage, J. S., Samuels, T. A., & Obare, S. O. (2019). Highly sensitive plasmonic metal nanoparticle-based sensors for the detection of organophosphorus pesticides. *Talanta*, 200, 218–227.
- Duan, D., Ye, J., Cai, X., & Li, K. (2021). Cobalt (II)-ion-exchanged Zn-bio-MOF-1 derived CoS/ZnS composites modified electrochemical sensor for chloroneb detection by differential pulse voltammetry. *Microchimica Acta*, 188, 1–10.
- Dufresne, A. (2012). *Nanocellulose: Potential reinforcement in composites*. Royal Society of Chemistry.
- El-Didamony, S. E., Kalaba, M. H., El-Fakharany, E. M., Sultan, M. H., & Sharaf, M. H. (2022). Antifungal and antibiofilm activities of bee venom loaded on chitosan nanoparticles: A novel approach for combating fungal human pathogens. *World Journal of Microbiology and Biotechnology*, 38(12), 244.
- Elhussein, E. A. A., Şahin, S., & Bayazit, Ş. S. (2018). Preparation of CeO₂ nanofibers derived from Ce-BTC metal-organic frameworks and its application on pesticide adsorption. *Journal of Molecular Liquids*, 255, 10–17.
- El-Moghazy, A. Y., Huo, J., Amaly, N., Vasylieva, N., Hammock, B. D., & Sun, G. (2020). An innovative nanobody-based electrochemical immunosensor using decorated nylon nanofibers for point-of-care monitoring of human exposure to pyrethroid insecticides. *ACS Applied Materials & Interfaces*, 12(5), 6159–6168.
- El-Sheikh, E. A., & Ashour, M. A. (2010). Biodegradation technology for pesticide toxicity elimination. In *Bioremediation technology: Recent advances* (pp. 167–205). Springer Netherlands.

- El-Sheikh, E. S. A., Li, D., Hamed, I., Ashour, M. B., & Hammock, B. D. (2023). Residue analysis and risk exposure assessment of multiple pesticides in tomato and strawberry and their products from markets. *Food*, 12(10), 1936.
- Farooq, U., Naz, F., Phul, R., Pandit, N. A., Jain, S. K., & Ahmad, T. (2020). Development of heterostructured ferroelectric SrZrO₃/CdS photocatalysts with enhanced surface area and photocatalytic activity. *Journal of Nanoscience and Nanotechnology*, 20(6), 3770–3779.
- Farooq, U., Ahmad, T., Naaz, F., & Islam, S. U. (2023). Review on metals and metal oxides in sustainable energy production: Progress and perspectives. *Energy & Fuels*, 37(3), 1577–1632.
- Fazeli-Nasab, B., Shahraki-Mojahed, L., Beigomi, Z., Beigomi, M., & Pahlavan, A. (2022). Rapid detection methods of pesticides residues in vegetable foods. *Chemical Methodologies*, 6(1), 24–40.
- Gamage, V., Nishshanka, U., Thiripuranathar, G., Priyantha, N., Gunewardene, S., & Jayanetti, S. (2024). Pesticides detection by nanotechnology-based sensors. In *Nanotechnology-based sensors for detection of environmental pollution* (pp. 215–236). Elsevier.
- Gao, Q., Chen, L., An, Z., Wang, Y., Yang, D., Wang, Z., et al. (2024). Development of an immunoassay based on a specific antibody for the detection of diphenyl ether herbicide fomesafen. *Science of the Total Environment*, 914, 169858.
- Ghareeb, S., Ragheb, D., El-Sheakh, A., & Ashour, M. B. A. (2022). Potential toxic effects of exposure to titanium silicon oxide nanoparticles in male rats. *International Journal of Environmental Research and Public Health*, 19(4), 2029.
- Ghareeb, S., Hagag, S., Ragheb, D., El-Sheakh, A., & Ashour, M. B. A. (2023). Gene expression analysis in male rat exposure to titanium dioxide nanoparticles. *Arab Journal of Nuclear Sciences and Applications*, 56(3), 17–26.
- Gonzalez-Techera, A., Kim, H. J., Gee, S. J., Last, J. A., Hammock, B. D., & Gonzalez-Sapienza, G. (2007). Polyclonal antibody-based noncompetitive immunoassay for small analytes developed with short peptide loops isolated from phage libraries. *Analytical Chemistry*, 79(23), 9191–9196.
- Guan, N., Li, Y., Yang, H., Hu, P., Lu, S., Ren, H., et al. (2021). Dual-functionalized gold nanoparticles probe based bio-barcode immuno-PCR for the detection of glyphosate. *Food Chemistry*, 338, 128133.
- Guo, J., Wong, J. X., Cui, C., Li, X., & Yu, H. Z. (2015). A smartphone-readable barcode assay for the detection and quantitation of pesticide residues. *Analyst*, 140(16), 5518–5525.
- Guo, M., Weng, X., Wang, T., & Chen, Z. (2017). Biosynthesized iron-based nanoparticles used as a heterogeneous catalyst for the removal of 2, 4-dichlorophenol. *Separation and Purification Technology*, 175, 222–228.
- Gyanjyoti, A., Guleria, P., Awasthi, A., Singh, K., & Kumar, V. (2023). Recent advancement in fluorescent materials for optical sensing of pesticides. *Materials Today Communications*, 34, 105193.
- Hammock, B. D., & Mumma, R. O. (1980). *Potential of immunochemical technology for pesticide analysis*. ACS Publications.
- Haq, A. U., Saeed, M., Muneer, M., Jamal, M. A., Maqbool, T., & Tahir, T. (2022). Biosorption of metribuzin pesticide by Cucumber (*Cucumis sativus*) peels-zinc oxide nanoparticles composite. *Scientific Reports*, 12(1), 5840.
- Hara, T. O., & Singh, B. (2021). Electrochemical biosensors for detection of pesticides and heavy metal toxicants in water: Recent trends and progress. *ACS ES&T Water*, 1(3), 462–478.
- Harmesen, M. M., & De Haard, H. J. (2007). Properties, production, and applications of camelid single-domain antibody fragments. *Applied Microbiology and Biotechnology*, 77, 13–22.
- Hou, X., Lei, S., Qiu, S., Guo, L., Yi, S., & Liu, W. (2014). A multi-residue method for the determination of pesticides in tea using multi-walled carbon nanotubes as a dispersive solid phase extraction absorbent. *Food Chemistry*, 153, 121–129.
- Hu, X., Cao, Y., Tian, Y., Qi, Y., Fang, G., & Wang, S. (2020). A molecularly imprinted fluorescence nanosensor based on upconversion metal-organic frameworks for alpha-cypermethrin specific recognition. *Microchimica Acta*, 187, 1–10.

- Huo, J., Li, Z., Wan, D., Li, D., Qi, M., Barnych, B., et al. (2018). Development of a nanobody-alkaline phosphatase fusion protein and its application in a highly sensitive direct competitive fluorescence enzyme immunoassay for detection of 3-phenoxybenzoic acid in urine. *Journal of Agricultural and Food Chemistry*, 66(43), 11284.
- Huong, N. T. M., Hoai, P. T. T., & Quyen, D. T. T. (2024). Enhanced removal of pesticide micropollutant and bacteria using solar light-assisted ag-doped TiO₂: Prospects for environmental and health impacts. *Environmental Geochemistry and Health*, 46(7), 229.
- Iqbal, A., Haq, A. U., Cerrón-Calle, G. A., Naqvi, S. A. R., Westerhoff, P., & Garcia-Segura, S. (2021). Green synthesis of flower-shaped copper oxide and nickel oxide nanoparticles via *Capparis decidua* leaf extract for synergic adsorption-photocatalytic degradation of pesticides. *Catalysts*, 11(7), 806.
- Islam, M. A., Amin, S. N., Rahman, M. A., Juraimi, A. S., Uddin, M. K., Brown, C. L., & Arshad, A. (2022). Chronic effects of organic pesticides on the aquatic environment and human health: A review. *Environmental Nanotechnology, Monitoring & Management*, 18, 100740.
- Ji, H., Xia, C., Xu, J., Wu, X., Qiao, L., & Zhang, C. (2020). A highly sensitive immunoassay of pesticide and veterinary drug residues in food by tandem conjugation of bi-functional mesoporous silica nanospheres. *Analyst*, 145(6), 2226–2232.
- Jiang, S., Sun, J., Xin, Z., Mao, H., Wu, X., & Li, Q. (2017). Visualizing distribution of pesticide residues in mulberry leaves using NIR hyperspectral imaging. *Journal of Food Process Engineering*, 40(4), e12510.
- Kamarudin, N. S., Jusoh, R., Setiabudi, H. D., Jusoh, N. W. C., Jaafar, N. F., & Sukor, N. F. (2019). Cymbopogon nardus mediated synthesis of ag nanoparticles for the photocatalytic degradation of 2, 4-dichlorophenoxyacetic acid. *Bulletin of Chemical Reaction Engineering & Catalysis*, 14(1), 173–181.
- Kamyabi, M. A., & Moharramezhad, M. (2021). A promising electrochemiluminescence herbicide sensor based on ternary nanocomposite and boron nitride quantum dots for trace analysis of tribenuron-methyl in environmental samples. *Microchemical Journal*, 168, 106518.
- Khan, W. S., Hamadneh, N. N., & Khan, W. A. (2016). Polymer nanocomposites—synthesis techniques, classification and properties. *Science and applications of Tailored Nanostructures*, 50, 51–67.
- Khan, I., Saeed, K., & Khan, I. (2019). Nanoparticles: Properties, applications and toxicities. *Arabian Journal of Chemistry*, 12(7), 908–931.
- Köhler, G., & Milstein, C. (1975). Continuous cultures of fused cells secreting antibody of predefined specificity. *Nature*, 256(5517), 495–497.
- Krishnasamy, L., Krishna, K., & Subpiramanyam, S. (2022). Photocatalytic degradation of atrazine in aqueous solution using La-doped ZnO/PAN nanofibers. *Environmental Science and Pollution Research*, 29(36), 54282–54291.
- Kumar, S., Karfa, P., Madhuri, R., & Sharma, P. K. (2018). Designing of fluorescent and magnetic imprinted polymer for rapid, selective and sensitive detection of imidacloprid via activators regenerated by the electron transfer-atom transfer radical polymerization (ARGET-ATRP) technique. *Journal of Physics and Chemistry of Solids*, 116, 222–233.
- Kumari, V., Sharma, S., Sharma, A., Kumari, K., & Kumar, N. (2021). Hydrothermal synthesis conditions effect on hierarchical ZnO/CuO hybrid materials and their photocatalytic activity. *Journal of Materials Science: Materials in Electronics*, 32, 9596–9610.
- Lateef, A., & Nazir, R. (2017). Metal nanocomposites: Synthesis, characterization and their applications. In *Science & application of tailored nanostructures* (pp. 239–256). One Central Press (OCP).
- Lavand, A. B., & Malghe, Y. S. (2015). Visible light photocatalytic degradation of 4-chlorophenol using C/ZnO/CdS nanocomposite. *Journal of Saudi Chemical Society*, 19(5), 471–478.
- Li, J., Sun, W., Qin, Y., Cui, P., Song, G., Hua, X., et al. (2021a). Inner filter effect-based immunoassay for the detection of acetamiprid using upconversion nanoparticles and gold nanoparticles. *Food and Agricultural Immunology*, 32(1), 740–753.

- Li, Z. F., Dong, J. X., Vasylieva, N., Cui, Y. L., Wan, D. B., Hua, X. D., et al. (2021b). Highly specific nanobody against herbicide 2, 4-dichlorophenoxyacetic acid for monitoring of its contamination in environmental water. *Science of the Total Environment*, 753, 141950.
- Li, D., Li, J., Wu, C., Liu, H., Zhao, M., Shi, H., et al. (2024). Smartphone-assisted colorimetric biosensor for the determination of organophosphorus pesticides on the peel of fruits. *Food Chemistry*, 443, 138459.
- Lim, S. Y., Shen, W., & Gao, Z. (2015). Carbon quantum dots and their applications. *Chemical Society Reviews*, 44(1), 362–381.
- Lin, L., Dong, T., Nie, P., Qu, F., He, Y., Chu, B., & Xiao, S. (2018). Rapid determination of thiabendazole pesticides in rape by surface enhanced Raman spectroscopy. *Sensors*, 18(4), 1082.
- Lin, Y., Jin, X., Khan, N. I., Owens, G., & Chen, Z. (2021). Efficient removal of As (III) by calcined green synthesized bimetallic Fe/Pd nanoparticles based on adsorption and oxidation. *Journal of Cleaner Production*, 286, 124987.
- Liu, K., Jin, Y., Wu, Y., & Liang, J. (2022a). Simple and rapid colorimetric visualization of tetramethylthiuram disulfide (thiram) sensing based on anti-aggregation of gold nanoparticles. *Food Chemistry*, 384, 132223.
- Liu, S., Liu, S. G., Jiang, W., Zhao, Q., Gao, W., & Shi, X. (2022b). Detection of organophosphorus pesticides using silver-coated gold nanoparticles. *ACS Applied Nano Materials*, 5(11), 16402–16412.
- Liu, M. L., Chen, Z. J., Huang, X. Q., Wang, H., Zhao, J. L., Shen, Y. D., et al. (2023). A bispecific nanobody with high sensitivity/efficiency for simultaneous determination of carbaryl and its metabolite 1-naphthol in the soil and rice samples. *Environmental Pollution*, 335, 122265.
- Ma, X., Ou, Q., Yuan, J., Yang, J., Xu, S., & Zhang, X. (2023). Multifunctional Fe-doped carbon dots and metal-organic frameworks nanoreactor for cascade degradation and detection of organophosphorus pesticides. *Chemical Engineering Journal*, 464, 142480.
- Mansouriieh, N., Sohrabi, M. R., & Khosravi, M. (2019). Optimization of profenofos organophosphorus pesticide degradation by zero-valent bimetallic nanoparticles using response surface methodology. *Arabian Journal of Chemistry*, 12(8), 2524–2532.
- Mejula, J. J., Jeevitha, S., Jyothipriya, K., Devi, G. R., & Kalaikumar, T. (2020). IoT based solution for monitoring of pollution through pesticides in fresh fruits and vegetables. *International Journal of Research in Engineering, Science and Management*, 3(56), 1040–1042.
- Mohammadi, Z. B., Zhang, F., Kharazmi, M. S., & Jafari, S. M. (2023). Nano-biocatalysts for food applications; immobilized enzymes within different nanostructures. *Critical Reviews in Food Science and Nutrition*, 63(32), 11351–11369.
- Mohapatra, L., Cheon, D., & Yoo, S. H. (2023). Carbon-based nanomaterials for catalytic wastewater treatment: A review. *Molecules*, 28(4), 1805.
- Moldovan, C., Firtat, B., Dinulescu, S., Brasoveanu, C., Ion, M., Codreanu, C., et al. (2017). Integrated platform for pesticides detection in food. In *2017 IEEE biomedical circuits and systems conference (BioCAS)* (pp. 1–4). IEEE.
- Nekooie, R., Shamspur, T., & Mostafavi, A. (2021). Novel CuO/TiO₂/PANI nanocomposite: Preparation and photocatalytic investigation for chlorpyrifos degradation in water under visible light irradiation. *Journal of Photochemistry and Photobiology A: Chemistry*, 407, 113038.
- Pabbi, M., Kaur, A., Mittal, S. K., & Jindal, R. (2018). A surface expressed alkaline phosphatase biosensor modified with flower shaped ZnO for the detection of chlorpyrifos. *Sensors and Actuators B: Chemical*, 258, 215–227.
- Parihar, A., Sharma, P., Choudhary, N. K., Khan, R., & Mostafavi, E. (2024). Internet-of-things-integrated molecularly imprinted polymer-based electrochemical nano-sensors for pesticide detection in the environment and food products. *Environmental Pollution*, 351, 124029.
- Parsaie, A., Baezat, M. R., & Rahbar, N. (2024). Evaluation of imidacloprid adsorption on a new activated carbon-based nanocomposite consisting of magnetite and copper oxide nanoparticles: Adsorption modelling, optimisation, and characterisation. *International Journal of Environmental Analytical Chemistry*, 104(3), 566–583.

- Pathania, D., Sharma, A., Kumar, S., Srivastava, A. K., Kumar, A., & Singh, L. (2021). Bio-synthesized Cu–ZnO hetero-nanostructure for catalytic degradation of organophosphate chlorpyrifos under solar illumination. *Chemosphere*, 277, 130315.
- Patle, T. K., Kurrey, R., Dewangan, K., & Shrivastava, K. (2020). Degradation, removal, and detection of pesticides using nanocomposites. In *Multifunctional hybrid nanomaterials for sustainable agri-food and ecosystems* (pp. 241–254). Elsevier.
- Pham, T. B., Hoang, T. H. C., Pham, V. H., Nguyen, V. C., Nguyen, T. V., Vu, D. C., et al. (2019). Detection of Permethrin pesticide using silver nano-dendrites SERS on optical fibre fabricated by laser-assisted photochemical method. *Scientific Reports*, 9(1), 12590.
- Phuithiang, P., & Kajitvichyanukul, P. (2019). Degradation of paraquat from contaminated water using green TiO₂ nanoparticles synthesized from *Coffea arabica* L. in photocatalytic process. *Water Science and Technology*, 79(5), 905–910.
- Premalatha, N., & Miranda, L. R. (2019). Surfactant modified ZnO–Bi₂O₃ nanocomposite for degradation of lambda-cyhalothrin pesticide in visible light: A study of reaction kinetics and intermediates. *Journal of Environmental Management*, 246, 259–266.
- Qi, Y., Chen, Y., Xiu, F. R., & Hou, J. (2020). An aptamer-based colorimetric sensing of acetamiprid in environmental samples: Convenience, sensitivity and practicability. *Sensors and Actuators B: Chemical*, 304, 127359.
- Rani, M., & Shanker, U. (2018). Degradation of traditional and new emerging pesticides in water by nanomaterials: Recent trends and future recommendations. *International journal of Environmental Science and Technology*, 15, 1347–1380.
- Rani, M., Shanker, U., & Jassal, V. (2017). Recent strategies for removal and degradation of persistent & toxic organochlorine pesticides using nanoparticles: A review. *Journal of Environmental Management*, 190, 208–222.
- Rani, M., Choudhary, S., Yadav, J., Keshu, & Shanker, U. (2022). Metal oxide-based nanocomposites for elimination of hazardous pesticides. In *Handbook of green and sustainable nanotechnology: Fundamentals, developments and applications* (pp. 1–26). Springer International Publishing.
- Rao, T. N., Balaji, A. P. B., Panagal, M., Parvatamma, B., Selvaraj, B., Panneerselvam, S., et al. (2020). Nanoremediation of dimethomorph in water samples using magnesium aluminate nanoparticles. *Environmental Technology & Innovation*, 20, 101176.
- Rasheed, T., Rizwan, K., Bilal, M., Sher, F., & Iqbal, H. M. (2021). Tailored functional materials as robust candidates to mitigate pesticides in aqueous matrices—A review. *Chemosphere*, 282, 131056.
- Rasheed, S., ul Haq, M. A., Ahmad, N., & Hussain, D. (2023). Smartphone-integrated colorimetric and microfluidic paper-based analytical devices for the trace-level detection of permethrin. *Food Chemistry*, 429, 136925.
- Rawtani, D., Khatri, N., Tyagi, S., & Pandey, G. (2018). Nanotechnology-based recent approaches for sensing and remediation of pesticides. *Journal of Environmental Management*, 206, 749–762.
- Rosero, T. M. S., & Camacho, D. H. (2017). Green preparation and characterization of tentacle-like silver/copper nanoparticles for catalytic degradation of toxic chlorpyrifos in water. *Journal of Environmental Chemical Engineering*, 5(3), 2524–2532.
- Saifuddin, N., Nian, C. Y., Zhan, L. W., & Ning, K. X. (2011). Chitosan-silver nanoparticles composite as point-of-use drinking water filtration system for household to remove pesticides in water. *Asian Journal of Biochemistry*, 6(2), 142–159.
- Saleh, T. A. (2022). Properties of nanoadsorbents and adsorption mechanisms. In *Interface science and technology* (Vol. 34, pp. 233–263). Elsevier.
- Saljooghi, A., Shamspur, T., & Mostafavi, A. (2021). Synthesis and photocatalytic activity of porous ZnO stabilized by TiO₂ and Fe₃O₄ nanoparticles: Investigation of pesticide degradation reaction in water treatment. *Environmental Science and Pollution Research*, 28, 9146–9156.

- Sanghavi, B. J., Hirsch, G., Karna, S. P., & Srivastava, A. K. (2012). Potentiometric stripping analysis of methyl and ethyl parathion employing carbon nanoparticles and halloysite nanoclay modified carbon paste electrode. *Analytica Chimica Acta*, 735, 37–45.
- Saran, S., Pravallika, P., Gopichand, K., Sudheer, U., & Vinod, G. V. (2024). Detection of pesticides in organic fruits and vegetables using IOT and ML. *International Journal of Engineering Research & Technology*, 13(2), S020022.
- Selmani, A., Kovačević, D., & Bohinc, K. (2022). Nanoparticles: From synthesis to applications and beyond. *Advances in Colloid and Interface Science*, 303, 102640.
- Serrano-Lázaro, A., Verdín-Betancourt, F. A., Jayaraman, V. K., de Lourdes López-González, M., Hernández-Gordillo, A., Sierra-Santoyo, A., & Bizarro, M. (2020). Efficient photocatalytic elimination of Temephos pesticide using ZnO nanoflowers. *Journal of Photochemistry and Photobiology A: Chemistry*, 393, 112414.
- Shabeer, T. P. A., Saha, A., Gajbhiye, V. T., Gupta, S., Manjaiah, K. M., & Varghese, E. (2015). Exploitation of nano-bentonite, nano-halloysite and organically modified nano-montmorillonite as an adsorbent and coagulation aid for the removal of multi-pesticides from water: A sorption modelling approach. *Water, Air, and Soil Pollution*, 226(3), 41.
- Shanaah, H. H., Alzaimoor, E. F., Rashdan, S., Abdalhafith, A. A., & Kamel, A. H. (2023). Photocatalytic degradation and adsorptive removal of emerging organic pesticides using metal oxide and their composites: Recent trends and future perspectives. *Sustainability*, 15(9), 7336.
- Sharma, A., Kumar, V., Shahzad, B., Tanveer, M., Sidhu, G. P. S., Handa, N., et al. (2019). Worldwide pesticide usage and its impacts on ecosystem. *SN Applied Sciences*, 1, 1–16.
- Singh, G., & Devi, T. (2024). Studies on photocatalytic mineralization of organic pesticides by bimetallic Cu–Zn nanoparticles derived from Zingiber officinale Roscoe (ginger) using green chemistry approach. *Environmental Science and Pollution Research*, 31(19), 27699–27708.
- Siva Rao, T., Segne, T. A., Susmitha, T., Balaram Kiran, A., & Subrahmanyam, C. (2012). Photocatalytic degradation of dichlorvos in visible light by Mg²⁺-TiO₂ nanocatalyst. *Advances in Materials Science and Engineering*, 2012(1), 168780.
- Su, Q., Shi, W., Huang, X., Yin, S., Yang, X., & Lu, X. (2023). Recent advances of nanobody applications in diagnosis and detection. *MedComm – Biomaterials and Applications*, 2(3), e54.
- Taghizade Firozjaee, T., Mehrdadi, N., Baghdadi, M., & Nabi Bidhendi, G. R. (2018). Application of nanotechnology in pesticides removal from aqueous solutions-a review. *International Journal of Nanoscience and Nanotechnology*, 14(1), 43–56.
- Taher, F. A., Moselhy, W. A., Mohamed, A. F., Didamony, S. E., Metwalley, K. M., & Zayed, A. B. (2017). Preparation and characterization of shrimp derived chitosan and evaluation of its efficiency as bee venom delivery for cancer treatment. *International Journal of Advanced Research*, 5(5), 370–388.
- Tao, Z., Deng, J., Wang, Y., Chen, H., Ding, Y., Hua, X., & Wang, M. (2019). Competitive immunoassay for simultaneous detection of imidacloprid and thiacloprid by upconversion nanoparticles and magnetic nanoparticles. *Environmental Science and Pollution Research*, 26, 23471–23479.
- Targhan, H., Rezaei, A., Aliabadi, A., Ramazani, A., Zhao, Z., Shen, X., & Zheng, H. (2024). Photocatalytic removal of imidacloprid pesticide from wastewater using CdS QDs passivated by CQDs containing thiol groups. *Scientific Reports*, 14(1), 530.
- Thorat, T., Patle, B. K., Wakchaure, M., & Parihar, L. (2023). Advancements in techniques used for identification of pesticide residue on crops. *Journal of Natural Pesticide Research*, 4, 100031.
- Tolasz, J., Henych, J., Štašný, M., Němečková, Z., Slušná, M. Š., Opletal, T., & Janoš, P. (2020). Room-temperature synthesis of nanoceria for degradation of organophosphate pesticides and its regeneration and reuse. *RSC Advances*, 10(24), 14441–14450.
- Tripathy, J., Mishra, A., Pandey, M., Thakur, R. R., Chand, S., Rout, P. R., & Shahid, M. K. (2024). Advances in nanoparticles and nanocomposites for water and wastewater treatment: A review. *Water*, 16(11), 1481.

- Truc, N. T. T., Duc, D. S., Van Thuan, D., Al Tahtamouni, T., Pham, T. D., Hanh, N. T., et al. (2019). The advanced photocatalytic degradation of atrazine by direct Z-scheme Cu doped ZnO/g-C₃N₄. *Applied Surface Science*, 489, 875–882.
- Vasylieva, N., Ahn, K. C., Barnych, B., Gee, S. J., & Hammock, B. D. (2015). Development of an immunoassay for the detection of the phenylpyrazole insecticide fipronil. *Environmental Science & Technology*, 49(16), 10038–10047.
- Viswanathan, S., & Manisankar, P. (2015). Nanomaterials for electrochemical sensing and decontamination of pesticides. *Journal of Nanoscience and Nanotechnology*, 15(9), 6914–6923.
- Vohra, T., Grover, H., Saxena, S., Verma, D. K., & Rameshwari, R. (2020). A review on nanoparticles based biosensors for pesticide detection in water. In *Importance & applications of nanotechnology* (pp. 1–9). MedDocs Publishers.
- Wang, K., & Li, J. (2021). Reliable SERS detection of pesticides with a large-scale self-assembled Au@ 4-MBA@ Ag nanoparticle array. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 263, 120218.
- Wing, K. D., Hammock, B. D., & Wustner, D. A. (1978). Development of an S-bioallethrin specific antibody. *Journal of Agricultural and Food Chemistry*, 26(6), 1328–1333.
- Xu, B., Wang, K., Vasylieva, N., Zhou, H., Xue, X., Wang, B., et al. (2021). Development of a nanobody-based ELISA for the detection of the insecticides cyantraniliprole and chlorantraniliprole in soil and the vegetable bok choy. *Analytical and Bioanalytical Chemistry*, 413, 2503–2511.
- Xu, L., Abd El-Aty, A. M., Eun, J. B., Shim, J. H., Zhao, J., Lei, X., et al. (2022). Recent advances in rapid detection techniques for pesticide residue: A review. *Journal of Agricultural and Food Chemistry*, 70(41), 13093–13117.
- Yadav, I. C., & Devi, N. L. (2017). Pesticides classification and its impact on human and environment. *Environmental Science and Engineering*, 6, 140–158.
- Yaneva, M., Ivanov, Y., Todorov, N., & Godjevargova, T. (2018). Magnetic-nanoparticles-based fluorescent immunoassay for individual and simultaneous determination of dichlorvos and paraoxon in milk. *Food and Agricultural Immunology*, 29(1), 228–243.
- Yang, D., Li, X., Li, X., Chen, J., Zhang, T., Lian, T., & Wang, H. (2024). Design and synthesis of nano-iron oxyhydroxide-based molecularly imprinted electrochemical sensors for trace-level carbendazim detection in actual samples. *Microchimica Acta*, 191(3), 163.
- Zaleska-Medynska, A., Marchelek, M., Diak, M., & Grabowska, E. (2016). Noble metal-based bimetallic nanoparticles: The effect of the structure on the optical, catalytic and photocatalytic properties. *Advances in Colloid and Interface Science*, 229, 80–107.
- Zhang, C., Qiu, M., Wang, J., & Liu, Y. (2023a). Recent advances in nanoparticle-based optical sensors for detection of pesticide residues in soil. *Biosensors*, 13(4), 415.
- Zhang, R., Zhang, L., Yu, R., & Wang, C. (2023b). Rapid and sensitive detection of methyl parathion in rice based on carbon quantum dots nano-fluorescence probe and inner filter effect. *Food Chemistry*, 413, 135679.
- Zhao, F., He, J., Li, X., Bai, Y., Ying, Y., & Ping, J. (2020). Smart plant-wearable biosensor for in-situ pesticide analysis. *Biosensors and Bioelectronics*, 170, 112636.
- Zou, B., Wang, Y., Zhou, S., Yang, S., & Wang, Y. (2022). Seed/ligand-cooperative growth of dense au nanospikes on magnetic microparticles for SERS applications. *Journal of Materials Chemistry C*, 10(9), 3368–3374.

Chapter 4

Potential Applications of Nanomaterials in Detection and Management of Plant Parasitic Nematode



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4.1 Introduction

Nematodes are roundworms that resemble threads and can survive in both fresh and saline water as well as soil. Plant parasitic nematodes (PPNs); there have been approximately 4100 species described to far, and these are supposed to be a substantial concern to the global food supply (Decraemer & Hunt, 2006). The World Bank projected in 2008 that global population would increase by 35% by 2050, accounting for both economic development and dietary choices. This would result in a 75% rise in food consumption (Keating et al., 2010). As a result, encouraging sustainable practices to improve resource efficiency has become a global environmental concern for pertinent stakeholders (Mokrini et al., 2018). They are one of the biggest limiting factors for major crops, parasitizing a wide variety of plant species, including dicots and monocots. It is estimated that they cause at least 80 billion dollars in crop losses year globally (Nicol et al., 2011).

Nematodes hold responsibility for 14.6% of crop losses in tropical and sub-tropical regions, while their contribution in developed nations has been reported to be 8.8% (Nicol et al., 2011). Cereal cyst nematodes (CCN) have the potential to decimate up to 90% of agricultural crops under favourable environmental circumstances (Nicol et al., 2011). Globally, potato cyst nematodes reduce potato yield by 9%. These South American worms are now major quarantine pathogens and have spread widely to every potato-growing region on Earth (Hockland et al., 2012).

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Nematodes that parasitize plants exhibit a diverse range of interactions with their host. They can be classified as endoparasites or ectoparasites based on the plant tissues they consume. While some PPNs are stationary, with an adult female clinging to the plant's roots and unable to migrate from the soil, others are migratory, moving with ease between soil and plant tissues. The specialized cells that surround the female head enable the sedentary endoparasites to feed. The stylet, an extension of the mouth that resembles a needle and is present in most PPNs species, aids in piercing the tissues of the host plant. In order to facilitate the plant cells' simple absorption into the nematode's intestines, they release certain enzymes into the tissues. Depending on where female is, the migratory adult female typically lays her eggs in the ground or among plants.

According to Abad et al. (2008), *Meloidogyne incognita* possesses a distinct set of putative genes that decrease plant immunity, detoxification, and defense systems while facilitating their survival within the plant host. The primary cause of root-knot nematodes' plant parasitic lifestyle is the large number of genes in their genomes that break down plant cell walls (Danchin et al., 2010). Because they are obligate biotrophs, *Meloidogyne* species must constantly inhibit host defensive mechanisms in order for their feeding structures to survive. *Meloidogyne incognita* release calreticulin, which aid in sequestering free calcium ions and so reduces calcium ion influx, as part of a defensive mechanism akin to that of plant pathogenic bacteria (Jaouannet et al., 2013). Complex plant diseases can result from the interaction of root knot nematodes with other pathogens such as *Rhizoctonia solani*, *Fusarium oxysporum*, and *Thielaviopsis basicola*. A gene found in *Meloidogyne* species resembles the rhizobial NodL gene, which causes legumes to develop nodules (McCarter et al., 2003). Legumes' nodulation signaling may be affected by nematode exudates, although certain mutant legumes that do not support regular nodulation are resistant to worm infections (Weerasinghe, 2004). Numerous nematode taxa secrete particular mixtures that include effectors and enzymes that break down cell walls, like xylanases (Haegeman et al., 2009), pectate lyases (Maier et al., 2013), and cellulases (Haegeman et al., 2009). These enzymes break down the cell walls of infected cells. Through modification of the host immune system's defense processes, the effectors may also be able to suppress the immune system. By extracting the cell contents through the nematode stylet, the species *Ditylenchus dipsaci* causes deformities in the infected plant tissues (Vovlas et al., 2011). Because the fourth generation juvenile's outer lipid layer keeps its body from losing water, this nematode has the unusual ability to withstand dry circumstances and freeze (Perry & Moens, 2011).

4.2 Current Challenges in Nematode Management

4.2.1 Preventive

To date, the EPPO has published maps showing the global distribution of nematode species deemed important for quarantine or commerce on a regular basis (Ornat et al., 2001). Because of the effectiveness of quarantines, major nematode pests have

not been introduced or allowed to spread locally or internationally, which has significantly reduced agricultural crop production costs globally (Haque & Khan, 2021). Other preventive measures, such as escape cropping, which is typically accomplished by planting later to take advantage of the host-free period, have shown promise in controlling certain crop nematode pests (Ornat et al., 2001).

Since exclusion keeps nematode pests from spreading to new areas, it has shown to be a very efficient and economical method of causing nematode damage on crops. Exclusion is mostly performed by diagnostic and quarantine. This long-standing method of pest control has stopped the spread of several commercially significant nematode pests, such as the virulent *Meloidogyne enterolobii*, from entering nations where they have not yet been identified.

4.2.2 Flooding

Nematodes in flooded soil typically die due to anaerobic conditions brought on by protracted flooding episodes. After protracted flooding periods of the wet season, the majority of paddy rice fields are often found to be nematode free in the following dry season. This technique has been used to successfully manage crop-damaging nematodes in a number of rice paddy fields. However, for flooding to be an effective management measure, the timing of flooding for each species of nematode pest must be deliberate. Furthermore, because flooding creates an anaerobic situation on soil structure, which has negative agronomic effects including low soil oxygen, it might not be the optimal strategy for managing nematodes on particular crops.

4.2.3 Using Deep Tillage to Manage Nematodes

Nematode populations can also be lowered by using soil management techniques like deep tillage, which entails turning the soil over to expose nematodes to the elements. By exposing nematodes to the environment, deep tillage is a soil management technique that can aid in reducing their populations. Nematodes are exposed to potentially hazardous conditions such as dryness and sunshine when the soil is disturbed. Nonetheless, this approach may have adverse effects on the quality of the soil and is not suggested in every circumstance. Deep tillage has the potential to degrade soil quality and lower crop yields due to soil erosion, organic matter loss, and soil structure disruption. Therefore, before using deep tillage as a nematode management method, it is crucial to thoroughly weigh the potential advantages and disadvantages of the practice. For preserving soil health and controlling nematode populations, low tillage or no-till methods may be more suitable and successful in some situations).

4.2.4 Generating Crops Resistant to Nematodes by Gene Editing

In order to modify the expression of genes involved in nematode resistance, this approach entails introducing particular alterations in a plant's DNA sequence (Abd-Elgawad, 2022a; Bairwa et al., 2022). For instance, scientists can alter already-existing genes to increase their efficacy against worm infestations or introduce mutations that activate genes involved in the plant's defense against nematodes. Gene editing presents a number of benefits over conventional breeding techniques in the development of nematode-resistant crops. It improves accuracy and efficiency by enabling researchers to focus on particular genes linked to nematode resistance. Furthermore, gene editing can speed up the creation of new crop varieties because it can take years to breed and test crops for resistance using traditional methods (Abd-Elgawad, 2022a).

The application of gene editing in crop development is still debatable despite its possible advantages, with some opponents questioning the morality and safety of genetically modified crops. Each nation has its own set of rules pertaining to the application of gene editing in agriculture. Consequently, it is imperative that the technology be utilized conscientiously and in compliance with moral and legal mandates (Turnbull et al., 2021).

4.2.5 Using Organic Additives to Manage Nematodes

Utilizing organic amendments like manure and compost can enhance soil health and promote the establishment of advantageous microorganisms, among other cultural practices (Mahmood et al., 2024). Nematode populations can be decreased by adding organic amendments to the soil to increase biological activity and soil fertility (Mukhtar et al., 2013; El-Deriny et al., 2020). Compost, for example, has been shown to boost the numbers of predatory mites that live in the soil and can feed on nematodes, so lowering their numbers.

Similarly, it has been demonstrated that applying manure reduces nematode populations by increasing nutrient availability and soil microbial activity (Roskopf et al., 2020). Plant growth may be hampered by the emission of volatile and non-volatile chemicals that occur when organic inputs break down. When it comes to organic amendments that release ammonia, soil microorganisms quickly convert ammonia into nitrites and nitrates through the process of nitrification. This lowers the pH of the soil and renders it unsuitable for plant growth (Galadima, 2015).

4.2.6 Biological Control

Biological control involves using living organisms or their byproducts to manage pests and has shown significant promise for the control of plant-parasitic nematodes

(PPNs) (Migunova & Sasanelli, 2021). As an eco-friendly alternative to hazardous chemical pesticides, biocontrol strategies offer sustainable solutions for reducing PPN populations (Shahid & Khan, 2019). Numerous studies have reported the effectiveness of soil microbial agents in nematode suppression (Gupta et al., 2022), and this approach is increasingly recognized worldwide as a viable substitute for chemical treatments (Saad et al., 2022). Biopesticides, derived from natural coevolutionary processes rather than synthetic chemistry, are designed to minimize environmental impact. Organisms such as actinomycetes, fungi, bacteria, and predatory nematodes—especially bacteria and fungi—have demonstrated high efficacy in nematode control (Migunova & Sasanelli, 2021). Due to health and environmental concerns, consumers are increasingly favoring food grown with biopesticides, which are considered as effective as synthetic nematicides.

Among microbial agents, bacterial genera including *Agrobacterium*, *Clostridium*, *Chromobacterium*, *Azotobacter*, *Burkholderia*, *Corynebacterium*, *Bacillus*, and *Serratia* have demonstrated notable potential for managing PPNs globally (Migunova & Sasanelli, 2021). Particular attention has been given to *Bacillus* and *Pseudomonas*, which are widely distributed and actively investigated for their biocontrol capabilities against root-knot nematodes (RKNs) (Dehghanian et al., 2020).

These bacteria suppress nematodes through mechanisms such as parasitism, competition, and antibiosis. Their effectiveness is linked to their ability to colonize plant surfaces, compete for nutrients and ecological niches, and produce toxins or nematicidal and antimicrobial compounds (Migunova & Sasanelli, 2021). Moreover, some bacteria can enhance plant defense responses by inducing systemic resistance (Raymaekers et al., 2020). The plant growth-promoting bacteria (PGPB) group has shown strong biocontrol potential, particularly against *Heterodera* (cyst) and *Meloidogyne* (root-knot) nematodes, underscoring their significance in integrated nematode management strategies (Gamalero & Glick, 2020).

4.2.7 Chemical Control

Because chemical control has an instant impact on nematode populations, it is a frequently employed management method against worms in agriculture. Chemicals called nematicides are used in crops when alternative management techniques might not be practical or efficient enough to reduce nematode infestations. They can be used on plant roots or soil to lower nematode numbers and minimize crop loss. To maximize effectiveness and reduce environmental impact, chemical control is frequently used in conjunction with other management measures, such as crop rotation and resistant crop types (Chen & Song, 2021).

Nematode control cannot be achieved by just detecting the nematodes and using the right nematicide; these measures are not long-term or permanent. Numerous chemical nematicides are costly, hazardous to people, animals, and the environment, and carcinogenic. They have also been shown to eventually degrade soil quality and

contaminate groundwater. Furthermore, the nematicide administered may become ineffective against nematodes due to unfavorable weather circumstances. As a result, a large number of chemical nematicides are already severely limited or prohibited globally (Collange et al., 2011). A few chemical nematicides have gained significant attention lately because of their decreased toxicity to soil species that are not their intended targets. All things considered, chemical control against nematodes in agriculture can be a useful management tool, but it must be applied cautiously and in concert with other tactics to minimize environmental damage and lower the likelihood of resistance development. The study of alternative, more environmentally friendly control strategies, such biological control, is essential to the advancement of nematology and the promotion of sustainable agricultural practices.

4.2.8 Fumigation

The use of clean plant material and agricultural equipment, heat treatment, crop rotation, and fumigation of afflicted crop fields are a few examples of conventional management techniques. Many growers additionally disinfect their seeds and bulbs in formaldehyde or hot water. To safeguard tomato plants from the destructive *Meloidogyne* species, a variety of management techniques have been used, including chemical control, soil solarization, and organic amendments. Among these tactics, chemical fumigants including chloropicrin, Telone II, Paladin (dimethyl disulfphide, or DMDS), and Vapam (metam sodium) were found to be somewhat effective but required buffer zones, were expensive, difficult to apply, and had lengthy re-entry periods. Ethanedinitrile (EDN) has been applied as a promising fumigant to prevent the spread and infection of *Meloidogyne hapla* while also increasing carrot output in Litol, Czech Republic. It was discovered that a number of environmental factors, including temperature, humidity, and soil characteristics, had an impact on the fumigant's effectiveness. Furthermore, inexperienced farmers were prohibited from fumigating the soils independently due to the acute toxicity of EDN. Long-term usage of these substances is anticipated to be restricted due to health and environmental concerns.

4.2.9 Nanotechnology in Nematode Control

The study and use of science, technology, and engineering at the nanoscale is known as nanotechnology (Khan et al., 2020). Because of the special qualities of nanoparticles that enable them to be adapted in vital sectors of human existence including medicine, pharmaceuticals, engineering, and agriculture, nanotechnology is a cutting-edge field of study with countless potential applications (Fabiya et al., 2020b). Nanotechnology has found widespread application in agriculture for the preservation of natural resources, crop production, and efficient management of

important pests and diseases (Fabiya et al., 2020a). The use of nanotechnology to manage nematodes has been reported to have produced notable results, despite the paucity of accessible reports. After 50 g of treatment, the rice cyst nematode population significantly decreased. In a similar vein, rice growth was enhanced and cyst nematode populations were decreased through the green manufacture of silver nanoparticles using *Eucalyptus officinalis* extracts (Fabiya et al., 2020b). When compared to the control group, groundnut plants treated with *Ficus mucoso*-mediated silver nanoparticles were observed to be more vigorous at harvest. Likewise, the use of *Cnidioscolus aconitifolius*-mediated silver nanoparticles significantly decreased the *M. incognita* infection of carrot plants. Regardless of *M. incognita* infestation, carrot plants with AgNPs sprayed at 50, 100, and 150 mol showed greater vegetative development and an excellent yield (Fabiya, 2021). The main goal of applying nanoparticles in agriculture is to fight diseases and pests. Nonetheless, several adverse consequences, such as diminished crop photosynthetic capacity, decreased biomass, fractured root caps, and damaged epidermis, have been recorded (El-Moneim et al., 2021). However, understanding how to use nanoparticles effectively is important.

4.3 Role of Nanotechnology in Nematode Management

Nematodes attack the root system of plants and consume nutrients, leading to reduced crop yield and potential plant death. Plants infected with nematodes are at risk of being further infected by various bacteria and fungi, affirming the importance of controlling the plant parasite. Crop rotation or planting trap crops that are later burned is the typical method used to manage nematode infestations in plants (Sikora & Roberts, 2018). Traditional breeding techniques are not very successful in combating nematodes because it takes many years to develop a resistant variety, and only a small number of crop plants naturally have nematode-resistant varieties. Conventional breeding techniques, biological control agents, and chemical nematocides can somewhat decrease nematode infestation but frequently fail to offer prolonged nematode control. The application of nanotechnology in plant pathology can develop plant disease management through the development of new tools for the rapid detection of pathogens using nano-based kits, and enhancing plants' nutrient absorption abilities. Additionally, nanoformulations offer a safer and more environmentally friendly approach to managing plant diseases and protecting root-system of plants Fig. 4.1 (El-Abeid et al., 2024).

4.3.1 Nanobiosensors for Nematode Detection

Sensing technologies form the backbone of early diagnostics, and biosensors are particularly gaining attention for their role in on-farm plant protection. Despite the

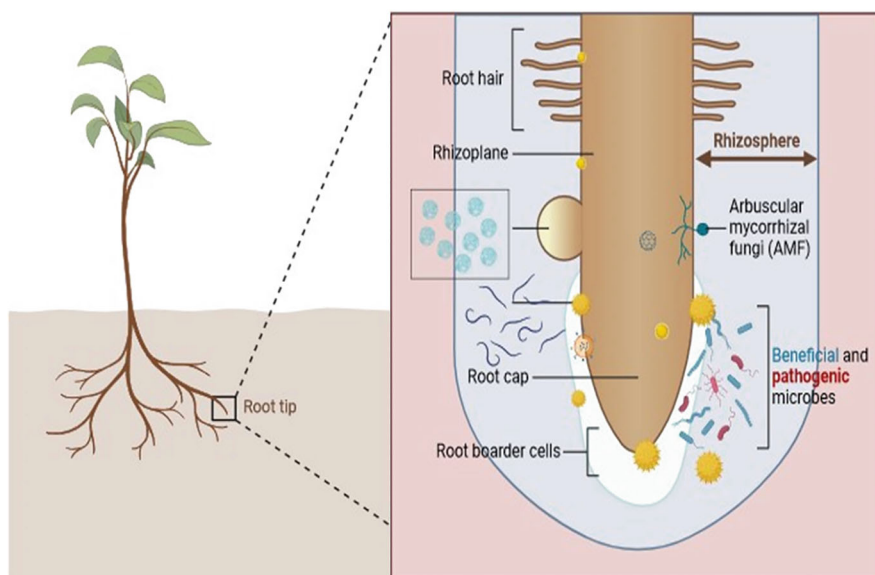


Fig. 4.1 Showing the role of nanoparticles in protection of plant root-system

abundance of instances demonstrating the use of nanosensors for detecting nematode pathogens, the utilization of nanotechnology in detecting plant pathogens is still in its early stages. There is no doubt that improvements in nano-biosensors for crops, due to advances in nanotechnology, combined with growing attention to biosensor-based applications, will facilitate advances in crop protection including the precision application of these agrochemicals. On the other hand, the concept of antibodies or enzymes as the optimal sensing materials has greatly driven the advancement of biosensors, creating a strong bond between nano-technology and biosensors, and leading to significant scientific and technological progress. (El-Abeid et al., 2024). Biosensors integrate a biological or biologically derived sensing element with a physical sensor component, with a report generation capability. The development of nano-biosensors has been driven by the evolution and progress in nanotechnology. Nano-scaled arrangements can enhance biosensor performance via the immobilization of sensory elements, such as the physical sensing of biological species, the hybridization process of molecules, the catalysis, and the interaction of biomolecules. The detection of nucleic acid is one of the main goals of detecting nematode pathogens and diseases. The conception of new-generation nano-biosensors with high sensitivities, specificities, and rapid detection in real-time opens unexplored scenarios in the early diagnostics of plant diseases (El-Abeid et al., 2024).

Biosensors are compact devices that use biological interactions to provide analytical information ranging from semi-quantitative to quantitative. These devices usually consist of three main components: a sensing element to detect the target, a signal transmission mechanism, and a means of amplifying the signal. Sensing

elements usually consist of proteins, receptor molecules, and biological components. Biosensors work by recognizing biological events through the interaction between the target analytic and sensing elements. The results are then converted into an electronic signal by transducer devices within the biosensor, simplifying complex biological responses into measurable optical, electrical, or mechanical signals.

Nanobiosensors are being used to detect plant nematodes. Carbon nanotube-based sensors are functionalized with specific antibodies to detect nematode proteins. Changes in nanotube electrical properties identify nematode presence (El-Abeid et al., 2024). Graphene sensors also use antibodies for detection, with changes in electrical or optical properties indicating the presence of *caenorhabditis elegans* nematode. Electrochemical sensors based on core-shell and nanowire composite is used for the detection of fenamiphos was utilized to control nematode. Nanoparticle sensors utilize gold or magnetic nanoparticles with antibodies for detection, using optical, magnetic, or electrochemical methods for identification. These sensors offer improved sensitivity, faster response times, and the potential for real-time monitoring of nematode populations in agriculture (El-Abeid et al., 2024). Research on nanobiosensors for nematode detection is ongoing for better nematode management and precision agriculture.

4.3.2 Nanotechnology in Nematode Management

Plant-parasitic nematodes were considered a significant threat to plants, leading to a 12% reduction in crop yield. However, there are no efficient nematicides accessible because of their toxicity and limited effectiveness against nematodes. Hence, in current times, nanotechnology is being used to combat plant-parasitic nematodes due to its multi-site mode of action against the nematodes without causing harm to plants.. Nanoparticles focus on multiple processes to affect nematodes and protect the host plants (Fig. 4.2). These mechanisms are represented (Fig. 4.2) as: **Direct toxicity**: Nanoparticles are able to directly harm nematodes. Such as Silver nanoparticles (AgNPs) in amounts ranging from 200–1500 mg/l have the ability to decrease the quantity of J2 larvae, prevent gall formation on roots, and inhibit nematode populations.

Oxidative stress Important mechanism of nanoparticles is caused by the production of reactive oxygen species (ROS), resulting in oxidative stress. Exposure to nanoparticles may enhance the activation of specific genes related to oxidative stress and repair the damage of DNA caused by this oxidative stress.

Nanoparticles have the ability to prevent the reproduction and development of the parasite nematode in the roots This impact can surpass the efficiency of recognized commercial nematicides.

Enhance a plant's immune system Some nanoparticles have the ability to enhance a plant's immune system, aiding in its ability to combat nematode infections.

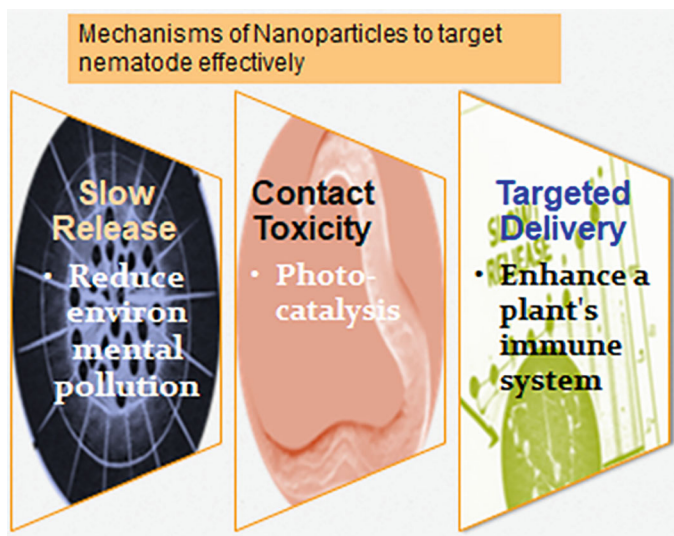


Fig. 4.2 Schematic diagram illustrates the mechanisms by which nanoparticles effectively target nematodes

Nematicides Nano-capsules filled with nematicidal substances have shown great effectiveness in combating internal parasitic nematodes. Nano nematicides enter the root system and stop the nematode from feeding or staying on the host plant. The various methods emphasize how nanomaterials can address nematode infestations, offering a hopeful option instead of traditional chemical nematicides.

Nanoparticles have emerged as effective bioactive agents against root-knot nematodes (*Meloidogyne* spp.) and as enhancers of host plant health. Equal-sized Cu, CuFe, and CuFeO₂ nanoparticles, synthesized via solvothermal methods, were evaluated for their nematicidal properties and impact on tomato plant growth. All tested formulations induced nematode paralysis and disrupted their life cycle, with CuFe NPs showing the highest efficacy ($EC_{50} = 0.03 \mu\text{g}$). Additionally, CuFe NP-treated tomato plants exhibited increased shoot and root biomass (Ch et al., 2019). Recent studies confirm that nanoparticles such as CuNPs, synthesized through both chemical and green methods, are effective against *Meloidogyne incognita*. Laboratory tests revealed significant nematicidal activity of CuNPs, particularly at concentrations of 100 and 200 mg/L against second-stage juveniles (J2). Nanotechnology presents a promising alternative to conventional nematicides, offering broad-spectrum activity against nematodes, fungi, and bacteria. Silver, silicon oxide, and titanium oxide nanoparticles have shown full control of root-knot nematodes under laboratory conditions. AgNPs, in particular, exhibit strong nematicidal effects against *M. incognita* with low phytotoxicity. Their mechanism involves disruption of cellular membranes, ATP synthesis, and induction of oxidative stress. Copper and iron nanoparticles synthesized using PEG8000 surfactant have also demonstrated activity against *M. incognita* and *M. javanica*, while Cu-based nanoparticles exhibit dual nematicidal and antifungal properties.

Comparative analysis of CuFe and Cu NPs revealed higher ionic release from CuFe NPs, which may enhance their bioactivity. When applied in soil, these nanoparticles can transform into bioavailable ions such as Cu^+ , Cu^{2+} , Fe^{2+} , and Fe^{3+} , facilitating plant uptake and systemic movement. The observed growth-promoting effects of CuFe NPs are attributed to synergistic interactions between copper and iron, especially the conversion of Fe^{3+} into the more plant-available Fe^{2+} form. Notably, CuFeO_2 (containing Fe^{3+}) did not promote growth, underscoring the role of Fe^{2+} . Prior studies have also linked treatments with metallic Cu and Fe NPs to increased sugar content in wheat seeds. Thus, CuFe nanoparticles hold dual potential as nematode suppressors and plant growth promoters (Ch et al., 2019).

4.4 Effect of Nanoparticles for Nematode Control

Nanotechnology can be employed in various manners to control agricultural nematodes. Applying nanoparticles (NPs) by soil drench or using a foliar spray is a straightforward and common method of NPs treatment, similar to how conventional pesticides are used to combat nematodes, pests, and microbial pathogens (Ardakani, 2013). Nevertheless, the direct exploitation of nanoparticles may also have an impact on non-target organisms, including bacteria responsible for mineral fixation and solubilization. In addition to its suppressive properties, nanoparticles have the potential to be used in transport and delivery systems for pesticidal chemicals. These compounds can include inhibitors of polyamine production, pheromones, SAR generation substances, and active components. The utilization of nanotechnology may lead to multi-site attack on nematodes without causing passive effect to plants. Nano based products such as nanosilver, and nanosulfur have been effectively utilized to combat plant nematodes.

4.4.1 Nanoparticles for Nematode Control

4.4.1.1 Metal Based Nanoparticles

Silver Nanoparticles

Silver nanoparticles (AgNPs) have garnered significant interest due to their strong conductivity, chemical stability, catalytic properties, and antibacterial activity. The role of AgNPs in managing plant diseases was first studied by Richards (1981). Silver nanoparticles have also demonstrated effectiveness in suppressing nematode activity (Roh et al., 2009).

These nanoparticles induce oxidative stress in targeted nematode cells (Table 4.1).

Furthermore, AgNPs disrupt multiple cellular mechanisms, including membrane permeability and ATP synthesis, in eukaryotes, prokaryotes, fungi, bacteria, and nematodes. Ardakani (2013) examined the toxicity of AgNPs on *M. incognita*

Table 4.1 Showing the nematocidal effects of some types of nanoparticles

Type of nanoparticles	Nanoparticles size	Plant nematode	Host plant	Effect	References
Gold nanoparticles (AuNPs)	20–45 nm	<i>Meloidogyne incognita</i>	Tomato	Inhibit nematode population in soil	Thakur et al. (2018)
Zinc oxide (ZnONPs)	≤50 nm	<i>Xiphinema vuitteneci</i>	Strawberry	Increase nematocidal effect	Sávoly et al. (2016)
Chitosan/poly- γ -glutamic acid (CS/ γ -PGA) nanocomposite	Different sizes with: 61 ± 4.5 and 56 ± 2.6 nm	<i>Bursaphelenchus xylophilus</i>	Pine tree	Increase nematocidal effect	Liang et al. (2018)
Copper nanoparticles (CuNPs)	100 nm	<i>Meloidogyne incognita</i>	Pine tree	Induce mortality level to J ₂	Mohamed et al. (2019)
Silver nanoparticles (AgNPs)	9.17–19 nm	<i>Meloidogyne javanica</i>	Eggplant	Inhibit J ₂ population	El-Shafeey et al. (2021)
Silver nanoparticles (AgNPs)	0.5–60 nm	<i>Meloidogyne incognita</i>	Eggplant	Inhibit egg hatching	Khan et al. (2021)
Silver nanoparticles (AgNPs)	60–112 nm	<i>Meloidogyne incognita</i>	Eggplant	Inhibited egg hatching	Nassar (2016a, b)
Silver nanoparticles (AgNPs)	60–112 nm	<i>Meloidogyne incognita</i>	Tomato	Induce mortality level to J ₂ and inhibited egg hatching	Kalaiselvi et al. (2017)
Silver nanoparticles (AgNPs)	2 nm	<i>Meloidogyne incognita</i>	Groundnut	Reduce nematode population in the soil	Fabiyi (2021)
Silver nanoparticles (AgNPs)	2 nm	<i>Meloidogyne graminis</i> , <i>Meloidogyne incognita</i>	Bermudagrass	Inhibited soil population	Cromwell et al. (2014)
Silver nanoparticles (AgNPs)	2 nm	<i>Meloidogyne incognita</i>	Bermudagrass	Induce mortality level	Ghareeb et al., (2022)
Silver nanoparticles (AgNPs)	2 nm	<i>Meloidogyne incognita</i>	Tomatoes	Increase nematocidal effect	Hassan et al. (2016a, b), Ghareeb et al., (2022)
AgNPs, silica oxide nanoparticles (SiO ₂ NPs) titanium oxide nanoparticles (TiO ₂ NPs)	20, 11–14 and 20 nm	<i>Meloidogyne incognita</i>	Tomatoes	Induce mortality level to J ₂	Ardakani (2013)

juveniles and found that AgNP treatments caused significant mortality in the nematode larvae. Due to their high degree of nematicidal action against root-knot nematodes, silver nanoparticles (AgNPs) can be used as substitutes for potentially hazardous chemical nematicides in valuable food crops (Cromwell et al., 2014). According to El-Deen and El-Deeb (2018), applying silver nanoparticles treatments to tomato crops in a greenhouse significantly decreased the number of *M. incognita* and enhanced plant growth characteristics.

Copper Oxide Nanoparticles

The use of copper Oxide nanoparticles (CuNPs) for managing plant associated diseases is a logical choice due to copper's long history of disease control (Elmer et al., 2018). CuO NPs have demonstrated effectiveness and specificity in suppressing the activity of numerous disease caused microbes (Tamayo et al., 2014). The fungicidal/bactericidal properties of CuO NPs were initially studied by Giannousi et al. (2013) under greenhouse conditions, where CuO NPs treatment proved to be the most effective in reducing leaf lesions at concentrations of 150–340 µg/mL. The effect of CuNPs on nematodes was examined in a study involving *Xiphinema index* infesting grapes conducted by Darago (2014). Given their antimicrobial properties, CuO NPs are expected to be effective against nematodes. Treatment with CuO NPs significantly suppressed the population of *M. incognita* under *in vitro* conditions (Kausar, 2022). The research study further recorded that the mortality of J2 stage nematodes was directly proportional to the concentration of CuNPs, with a concentration of 0.2 g NPs/L resulting in 100% mortality of the nematode juveniles. Some studies investigated the role of CuFe NPs against *Meloidogyne* spp. and their effect on the growth of nematode-infested plants (Ch et al., 2019). They reported that a 0.03 µg CuFe NPs was the most efficient concentration for suppressing nematodes and increasing the fresh weight of tomato plant shoots and roots.

Zinc Oxide Nanoparticles

Numerous studies have investigated the antimicrobial properties of zinc nanoparticles (ZnO NPs) against plant pathogens (Malandrakis et al., 2019). These nanoparticles have demonstrated inhibitory effects on bacteria, as well as fungi such as *Alternaria alternata*, *Fusarium oxysporum*, *Sclerotinia sclerotiorum*, *Botrytis cinerea*, *Penicillium expansum*, *Rhizopus stolonifera*, *Rhizoctonia solani*, and *Mucor plumbeus* under *in vitro* conditions (Sardella et al., 2017). Additionally, ZnO NPs have shown effectiveness against the root-knot nematode *Meloidogyne incognita*. Furthermore, the application of ZnO NPs has been reported to enhance seed germination, seedling vigor, and overall plant growth in groundnut (Prasad et al., 2012). In particular, a concentration of 0.10 mg/mL of ZnO NPs resulted in the greatest reduction in the multiplication of *Meloidogyne javanica* and the formation of galls, outperforming graphene oxide (Siddiqui et al., 2019). Gupta et al. (2015) also observed a decrease in nematode multiplication and galling when plants were sprayed with ZnO NPs. It is postulated that the ZnO NPs may have penetrated the nematode cuticle and hypodermis, thereby affecting lipids, glycogen, and mucopolysaccharides, which in turn resulted in distorted juvenile forms of *M. javanica*.

4.4.2 Nanoemulsions for Nematode Control

Plant parasitic nematodes pose a significant threat to economically important crops worldwide. However, controlling nematode populations is a challenging task, as the use of conventional insecticides can have detrimental effects on both living organisms and the environment. Therefore, it is crucial to develop alternative pest management strategies that are not only effective in combating nematodes but also environmentally safe.

One promising approach is the utilization of nanoemulsions, particularly those produced through the greatest energy technique, which demonstrates exceptional speed and efficiency in generating nano droplets with small size dispersion (Ghosh et al., 2014). Research has shown that monoterpenes, the primary constituents of essential oils, exhibit potent antibacterial properties when incorporated into nanoemulsions (Abdelrasoul et al., 2020). Several nanoemulsions containing monoterpenes, including cinnamaldehyde, citral, geraniol, (R)-carvone, and pulegone, have exhibited significant nematocidal activity against the root-knot nematode, *Meloidogyne javanica*, resulting in reduced egg hatching and increased mortality of juvenile nematodes (Abdel Rasoul & El-Habashy, 2021). Furthermore, the application of these nanoemulsions has led to a substantial reduction in root galls, egg masses, and overall population of *M. javanica*. While the exact mode of action of monoterpenes and essential oils on nematodes remains unknown, it has been observed that certain volatile oils exhibit carcinogenic activity in *Drosophila melanogaster* by activating octopaminergic receptors and inhibiting GABA receptors (Kostyukovsky et al., 2002).

4.4.3 Nanocarriers for Nematode Control

Formulations are essential to obtain more sustainable and multifunctional technologies. In this sense, nanotechnology-based tools—i.e. nanocarriers such as metallic nanoparticles, polymeric nanoparticles, nanoemulsions, among others—can carry compounds, extracts, or blenders resulting in a more controlled release and in a lesser amount of material to be used for phyto-nematodes control. In this regard, different types of nanoparticles such as carbon, silica (Barik et al., 2008), chitosan nanoparticles, solid lipid nanoparticles (SLN) (Borel & Sabliov, 2014), and layered double hydroxide (LDH) nanosheets (Mosa & Youssef, 2021) nanosheets have been utilized as nanocarriers for plant disease management. The establishment of a quality system is fundamental to obtain natural sources, residues, or blends and their formulations with reproducibility, repeatability, reliability, stability, efficiency resulting in safe food and customer satisfaction. Thus, this strategy will follow quality regulatory mechanisms that aim to increasingly meet the demands of society, the media, and national/international trade, which currently calls for safe food products with a environmental impact. On the other hand, there are two major

processes through which the advantages of application of nanomaterial or NPS can be obtained in order to estimate the possibility and usage of NPS in plant disease controlling, especially regarding the phytonematodes management:

1. Direct effect on pathogens when NPs are applied alone and used as protectants or applied in the form of nanopesticides by formulating nanomaterials using nanocarriers for insecticides, fungicides, herbicides, and RNA interference (RNAi).
2. Effect of nanomaterials or NPs on the physiological and biochemical activities of pathogens/microorganisms since nanomaterials are highly reactive substances due to their high surface-to-volume ratio.

4.5 Applications of Nanotechnology in Nematode Management

Certainly, Nanotechnology offers promising solutions for managing plant-parasitic nematodes. These organisms cause significant economic losses in agriculture. We will explore their applications below:

1. Nano-Bioparticles and Nanoparticles

Nanotechnology involves the use of nanobioparticles, green nanoparticles, and metal nanoparticles to control nematodes. These nanocompounds can penetrate the nematode body, disrupting their feeding and establishment on host plants. For example, Rupak et al. (2024) discovered that green silver nanoparticles have been effective in controlling root-knot nematodes and reducing phytotoxicity in eggplants. Fe_3O_4 nanoparticles have also shown promise by reducing nematode mobility and inducing apoptosis in *Caenorhabditis elegans* (Rupak et al., 2024).

2. Application Methods

Nanoparticles can be applied through soil drenching or foliar spray, similar to conventional pesticides. By targeting nematodes directly, nanotechnology provides an innovative approach to nematode management.

3. Economic Impact

The International *Meloidogyne* project estimates that nematodes cause annual losses of 78 billion US dollars in developed countries and over 100 billion in developing countries. Traditional controls are often insufficient, necessitating novel approaches like nanotechnology (Sabry, 2019).

In summary, nanotechnology holds great potential for sustainable and effective nematode management. Researchers continue to explore innovative formulations to protect crops and enhance agricultural productivity (Abd-El salam & Prasad, 2019).

4.5.1 *Nano-based Nematicides*

Here's a summary of the latest advancements in nano-based nematicides for nematode management:

- **Bioactivated Nematicides:** Researchers have developed nematicides containing the imidazothiazole chemical group. These compounds, called selectivins, are benign precursors that become lethal when activated in nematode tissue, offering remarkable selectivity for nematodes over other species.
- **Plant Virus Nanoparticles:** Engineers at UC San Diego have created nanoparticles from plant viruses to deliver pesticide molecules deep into the soil. This method targets the root zone where nematodes cause damage, potentially reducing pesticide use and environmental toxicity.
- **Nanoparticle Efficacy:** Various nanoparticles have shown potential as effective nematicides, making them a suitable option for controlling plant nematode infections
- **Next-Generation Nematicides:** Compounds like fluensulfone, fluopyram, and fluazaindolizine are highlighted as promising next-generation nematicides.

The Function of Nanoparticles as Nematicides

These innovations represent a significant step forward in the selective and sustainable management of nematodes in agriculture. Nanoparticles as nematicides offer a fascinating approach to controlling nematode populations. Let's dive into the details:

Size Matters Nanoparticles are incredibly small, typically ranging from 1 to 100 nm in diameter. Their tiny size allows them to interact with biological systems in unique ways. When applied to soil, nanoparticles can penetrate nematode tissues more effectively than larger particles.

Mechanisms of Action

1. **Physical Disruption:** Nanoparticles can physically damage nematodes. Their sharp edges or surfaces can cut through the nematode's protective cuticle, leading to desiccation or internal damage.
2. **Chemical Toxicity:** Some nanoparticles release toxic ions or molecules. For instance:
 - **Silver Nanoparticles (AgNPs):** These release silver ions (Ag^+), which interfere with nematode enzymes and disrupt cellular processes.
 - **Copper Nanoparticles (CuNPs):** Copper ions (Cu^{2+}) can damage nematode tissues.
 - **Zinc Oxide Nanoparticles (ZnO NPs):** ZnO NPs release zinc ions (Zn^{2+}) that affect nematode metabolism.
3. **Electrostatic Interactions:** Nanoparticles can adhere to nematode surfaces due to electrostatic forces. This disrupts their movement and feeding behavior.

4. **Surface Charge:** The surface charge of nanoparticles influences their interaction with nematodes. Positively charged nanoparticles may bind to negatively charged nematode surfaces, affecting their physiology.

Delivery Systems

- **Encapsulation:** Nematicidal compounds (such as essential oils or chemical pesticides) can be encapsulated within nanoparticles. These nanoparticles act as carriers, releasing the active ingredients gradually.
- **Targeted Delivery:** Researchers are exploring ways to specifically target nematodes using functionalized nanoparticles. These nanoparticles could home in on nematode-infested roots or soil regions.

4.5.2 Nano-based Nematode Detection

Nanotechnology offers innovative solutions for the detection and management of nematode infestations in agriculture. Here are some key points about nano-based nematode detection:

- **Nanobiosensors:** Utilize nanosensors conjugated with nematode biomarkers for quick and easy detection of plant diseases caused by nematodes as discovered with El-Abeid et al. (2024).
- **Specificity:** Target specific nematode proteins like MiPFN3, which is unique to root-knot nematodes, ensuring minimal impact on non-target organisms (El-Abeid et al., 2024).
- **Early Detection:** Nanobiosensors enable early diagnosis of nematode presence, allowing for timely management and control measures.
- **DNA Nanobiosensors:** DNA molecules have been utilized as nanobiosensors for the accurate and fast detection of nematode diseases, contributing to the early diagnosis and management of these pests.
- **Nano-Sensor Types:** There are chemical, mechanical, and biological nanosensors, each with specific applications in disease diagnosis and pest management.

The integration of nanosensors in agriculture promotes sustainable practices by improving crop productivity and reducing disease losses (El-Abeid et al., 2024). Nano-sensors offer high stability, specificity, sensitivity, and cost-effectiveness, making them a valuable tool in agriculture and environmental monitoring. These nano-sensors represent a significant advancement in the field of plant nematode management. As well as the advancements in nanotechnology could significantly enhance the efficiency of nematode management in crops, leading to better yield and healthier plants. For more detailed information, you can refer to the articles provided in the search results (El-Abeid et al., 2024).

4.5.3 *Nano-based Nematode Resistance Enhancement*

4.5.3.1 Use of Nanomaterials for Delivering Nematode-Resistant Genes

Nanomaterials have not been specifically mentioned in the provided sources for delivering nematode-resistant genes. However, genetic improvement of plants for nematode resistance via traditional breeding or genetic engineering is a common approach that has been discussed. It is important to note that there are diverse mechanisms of resistance in plants, and the use of R-genes can enhance crop productivity and control nematode populations (Abd-Elgawad, [2022a](#)).

4.5.3.2 Utilization of Nanoscale Delivery Systems for Targeted Nematode Control

Nanoscale delivery systems, such as silica nanoparticles, have been explored for pesticide delivery in agriculture to improve efficiency and reduce environmental impact. These systems can enhance the delivery of biopesticides to specific targets, increasing effectiveness while minimizing side effects. However, the use of certain nanoparticles, like gold or iron oxide-based ones, can be costly and environmentally unfriendly, limiting their widespread application in agro-biotechnological fields. Silica nanoparticles have shown promise due to their stability, versatility, and low cost, making them a potential nano-pesticide delivery system for agricultural use (Safeena & Zakeel, [2020](#)). Studies have demonstrated the effectiveness of silica nanoparticles in enhancing the antifeedant potential of terpenes against insects and improving the photostability of pesticides like avermectin (Jena et al., [2024](#)). While silica nanoparticles have been extensively researched for agricultural applications, more studies are needed to explore their feasibility in delivering proteic biopesticides efficiently. The controlled release of nanopesticides can offer targeted delivery to combat pests like nematodes, with nanocarriers improving adhesion, solubility, and bioactivity of pesticides. Visual tracking markers, such as fluorescent nanopesticides, can aid in monitoring pesticide transport and effectiveness in controlling nematode infestations. Overall, nanoscale delivery systems hold promise for targeted nematode control in agriculture, but further research is needed to optimize their efficiency and practicality.

4.5.3.3 Development of Nanosensors for Monitoring Nematode Infestation Levels

Nanosensors have been developed for monitoring pH levels in *Caenorhabditis elegans*, but specific nanosensors for monitoring nematode infestation levels have not been mentioned in the provided sources (El-Abeid et al., [2024](#)).

4.6 Environmental Implications of Nano-biotechnological Nematode Management

The control of nematodes has depended on chemical pesticides, which may cause negative effects on the environment. Recently, there has been increasing interest in using nanobiotechnology strategies to achieve more sustainable nematode management. Whereas, nematode management using nanotechnology involves the use of nanomaterials for nematode management. This also may include the use of nanoparticle-based nematicides, which can target and eliminate nematodes more efficiently. In addition, researchers are developing nanoparticles loaded with natural nematicidal compounds (such as plant extracts and bacterial toxins) to enhance their targeted delivery and efficacy against nematodes. Nano nematicides employ small doses with specific properties to effectively target nematodes while minimizing harm to the environment and other organisms through the contact toxicity of nematodes. Nanopesticides are designed to precisely target nematodes while minimizing harm to beneficial organisms. The surface charge of nanoparticles, such as silver, copper, and zinc oxide, can affect their interaction with nematodes. Controlled release of active ingredients ensures long-lasting effectiveness, with different types of nano-based nematicides made from mineral-based nanoparticles, carbon nanotubes, polymeric nanoparticles, and essential oils. These nanoformulations enhance delivery and reduce environmental impact (Ghareeb et al., 2022). Advantages of nano nematicides include precision targeting, reduced environmental pollution, enhanced efficacy, and resistance management. Challenges include safety evaluation for humans, animals, and ecosystems, understanding long-term effects, and establishing regulations for safe use. Ongoing research explores the immunostimulatory effects of nanoparticles on plants and the development of nano nematicides for effective nematode management in crops (Ghareeb et al., 2022).

- **Potential benefits for the environment:**

Nano-technological approaches can provide environmental advantages over traditional chemical nematicides. By Reducing chemical pollution and damage. and Increasing accuracy and efficiency in combating nematodes may lead to a shortage of the required active substances. As well as using environmentally friendly natural materials instead of commercial chemicals.

- **Potential risks to the environment:**

However, there are potential environmental risks that must be taken also into consideration. For instance, Potential toxicity and the presence of some nanomaterials in the environment in the long term. Additionally, unexpected consequences for soil organisms not targeted by biological control agents. The possibility of developing nematode resistance against biological nanocontrol methods in the future (Sabry, 2019).

Many researchers explore regulations, risk assessment models, and ethical issues in nanobiotechnology fields. For instance, it examined frameworks for managing risks associated with nanomaterials and suggested a versatile approach at multiple levels. Another study deals with efficient tactics for managing the risks of nanomaterials in the. Additionally, examines policy and ethics when evaluating risks associated with nanomaterials. Lastly, all studies discuss the difficulties and inquiries involved in utilizing the conventional risk assessment model for nanomaterials. These papers offer important observations on managing risks and ethical issues in the quickly progressing area of nanobiotechnology.

4.7 Future Perspectives and Challenges

While nanoparticles offer promise, their environmental impact must be carefully evaluated. Some concerns include potential toxicity to non-target organisms and long-term effects on soil health. Researchers are working on biodegradable nanoparticles to minimize environmental risks. In summary, nanoparticles as nematicides combine physical, chemical, and biological interactions to combat nematodes effectively. As research continues, we hope to develop safer and more sustainable solutions for nematode management.

There are some key challenges in developing safe and effective nematicides:

- **Environmental and Health Concerns:** The use of chemical nematicides has been associated with ecological contamination and adverse effects on human health, non-target beneficial organisms, and the development of resistance-breaking pathotypes, it was in a line with findings indicated in (Abd-Elgawad, 2022b).
- **Sustainable Agriculture:** There is a pressing need for more reliable and safer techniques to manage plant pests/pathogens, as dissatisfaction with synthesized pesticides like chemical nematicides is increasing (Abd-Elgawad, 2022b).
- **Selective Control:** Finding nematicides that are selective for nematodes without being toxic to non-target organisms is a significant challenge. New strategies with improved selectivity are essential to ensure global food security.
- **Organic Alternatives:** The increasing interest in protecting the environment and human health has prompted research on sustainable approaches that require fewer synthetic nematicides and fertilizers.

Nanotechnology offers innovative solutions for managing plant-parasitic nematodes, which are a significant threat to agriculture. Here are some key applications:

- **Nano-pesticides:** Utilizing nano-capsules, nanoparticles, and nano-suspension pesticides can effectively target nematodes as mentioned by Sabry (2019).
- **Nematicidal Compounds:** Nanocompounds can penetrate plant roots, preventing nematodes from feeding or establishing themselves.

- **Nanomaterials:** These can directly penetrate nematodes, leading to their death within a short period.
- **Nanosensors:** Advanced sensors can detect nematode populations in soil or plant tissue with precision.

These nanotechnology applications not only help in controlling nematodes but also reduce environmental impact compared to traditional methods. Implementing nano-based solutions for nematodes presents both opportunities and challenges. Let's delve into some of the key challenges:

1. **Nematode Size and Detection:** Nematodes are tiny organisms, making their detection challenging. Traditional methods struggle due to their small size, high numbers in samples, and lack of distinct morphological characteristics (Hudie et al., 2023).
2. **Specificity and Selectivity:** Developing nano-biosensors that can specifically target nematode biomarkers while minimizing harm to non-target organisms is crucial. For instance, inhibiting proteins unique to nematodes (like MiPFN₃) requires high specificity (El-Abeid et al., 2024).
3. **Soil Sterilization:** Once plant-parasitic nematodes establish themselves in the soil, control becomes difficult. Soil sterilization may be necessary, but it's an extreme measure with potential ecological consequences (Sabry, 2019).
4. **Formulation Challenges:** Creating effective nano-based pesticide formulations (such as nano-capsules, nanoparticles, and nano-suspensions) requires overcoming stability, toxicity, and delivery challenges (Sabry, 2019).
5. **Cost and Scalability:** Developing and implementing nanotechnology solutions can be expensive. Ensuring scalability and affordability for widespread adoption is essential (Tiwari et al., 2023).
6. **Regulatory Approval:** New technologies must undergo rigorous safety and efficacy assessments before widespread use. Regulatory approvals can be time-consuming and complex (Sabry, 2019).

4.8 Conclusion

Recent research highlights the growing potential of nanotechnology in diagnosing and managing plant diseases, particularly those caused by pathogenic phytonematodes such as root-knot and cyst nematodes. The application of various nanoparticles and nanocarriers has proven effective in reducing nematode-induced damage in economically important crops. Advanced nanomaterials—such as nanocapsules and nanotubes—are being utilized for the targeted delivery of biopesticides, resistance inducers, and enzyme inhibitors directly to infected plant tissues and soils. Furthermore, metal- and enzyme-based nanosensors are increasingly used for disease detection and pesticide residue analysis.

In parallel, biotechnological approaches are being developed to enhance host plant resistance against nematodes. Strategies include the genetic engineering of

plants using resistance genes, manipulation of nematode housekeeping genes, and the induction of protease inhibitors. Among these, RNA interference (RNAi)-based gene silencing of nematode effector proteins offers a promising tool for achieving durable resistance and minimizing yield losses.

References

- Abad, P., Gouzy, J., Aury, J. M., Castagnone-Sereno, P., Danchin, E. G., Deleury, E., et al. (2008). Genome sequence of the metazoan plant-parasitic nematode *Meloidogyne incognita*. *Nature Biotechnology*, 26(8), 909–915.
- Abdel Rasoul, M. A., & El-Habashy, D. E. (2021). Nematicidal activity of some nanoemulsions of monoterpenes on tomato root-knot nematodes (*Meloidogyne javanica*). *Journal of Plant Protection and Pathology*, 12(9), 655–661.
- Abd-Elgawad, M. M. M. (2022a). Understanding molecular plant–nematode interactions to develop alternative approaches for nematode control. *Plants*, 11(16), 2141.
- Abd-Elgawad, M. M. M. (2022b). Exploiting plant–phytonematode interactions to upgrade safe and effective nematode control. *Life*, 12, 1916. <https://doi.org/10.3390/life12111916>
- Abdelrasoul, M. A., Eid, A. R., & Badawy, M. E. (2020). Preparation, characterizations and antibacterial activity of different nanoemulsions incorporating monoterpenes: In vitro and in vivo studies. *Archives of Phytopathology and Plant Protection*, 53(7–8), 310–334.
- Abd-Elsalam, K. A., & Prasad, R. (2019). Nanobiotechnology applications in plant protection, nanotechnology in the life sciences, springer nature. *Science*, 2, 291.
- Ardakani, A. S. (2013). Toxicity of silver titanium and silicon nanoparticles on the root-knot nematode *Meloidogyne incognita* and growth parameters of tomato. *Nematology*, 15(6), 671–677. <https://doi.org/10.1163/15685411-00002710>
- Bairwa, A., Venkatasalam, E. P., Subhash, S., & Dipta, B. (2022). Management of potato cyst nematodes (*Globodera* spp.) using biotechnological approaches. In *Genetic methods and tools for managing crop pests* (pp. 343–360). Springer Nature.
- Barik, T. K., Sahu, B., & Swain, V. (2008). Nanosilica—from medicine to pest control. *Parasitology Research*, 103, 253–258.
- Borel, T., & Sabliov, C. (2014). Nanodelivery of bioactive components for food applications: Types of delivery systems, properties, and their effect on ADME profiles and toxicity of nanoparticles. *Annual Review of Food Science and Technology*, 5, 197–213.
- Ch, G., Ntalli, N., Menkissoglu-Spiroudi, U., & Dendrinou-Samara, C. (2019). Essential metal-based nanoparticles (copper/iron NPs) as potent nematicidal agents against *Meloidogyne* spp. *Journal of Nano Research*, 1(2), 44–58.
- Chen, J. X., & Song, B. A. (2021). Natural nematicidal active compounds: Recent research progress and outlook. *Journal of Integrative Agriculture*, 20(8), 2015–2031.
- Collange, B., Navarrete, M., Peyre, G., Mateille, T., & Tchamitchian, M. (2011). Root-knot nematode (*Meloidogyne*) management in vegetable crop production: The challenge of an agronomic system analysis. *Crop Protection*, 30(10), 1251–1262.
- Cromwell, W. A., Yang, J., Starr, J. L., & Jo, Y. K. (2014). Nematicidal effects of silver nanoparticles on rootknot nematode in Bermudagrass. *Journal of Nematology*, 46(3), 261–266.
- Danchin, E. G., Rosso, M. N., Vieira, P., de Almeida-Engler, J., Coutinho, P. M., Henrissat, B., & Abad, P. (2010). Multiple lateral gene transfers and duplications have promoted plant parasitism ability in nematodes. *Proceedings of the National Academy of Sciences*, 107(41), 17651–17656.
- Darago, A. (2014). *The distribution of dagger nematodes species in Hungarian wind regions and newest control options* [PhD thesis]. Universidad Pannonia Georgikon.
- Decraemer, W., & Hunt, D. J. (2006). *Structure and classification* (pp. 3–32). CABI.

- Dehghanian, S. Z., Abdollahi, M., Charehgani, H., & Niazi, A. (2020). Combined of salicylic acid and *Pseudomonas fluorescens* CHA0 on the expression of PR1 gene and control of *Meloidogyne javanica* in tomato. *Biological Control*, 141, 104134.
- El-Abeid, S. E., Mosa, M. A., Boudaden, J., et al. (2024). Nanobiosensors: A powerful technology for early detection of plant parasitic nematodes. *Sensing and Imaging*, 25, 23. <https://doi.org/10.1007/s11220-024-00470-9>
- El-Deen, A. H. N., & El-Deeb, B. A. (2018). Effectiveness of silver nanoparticles against root-knot nematode, *Meloidogyne incognita* infecting tomato under greenhouse conditions. *The Journal of Agricultural Science*, 10, 148–156.
- El-Deriny, M. M., Ibrahim, D. S., & Mostafa, F. A. (2020). Organic additives and their role in the phytoparasitic nematodes management. In *Management of phytonematodes: Recent advances and future challenges* (pp. 73–93). Springer.
- Elmer, W., De La Torre-Roche, R., Pagano, L., Majumdar, S., Zuverza-Mena, N., Dimkpa, C., et al. (2018). Effect of metalloid and metal oxide nanoparticles on Fusarium wilt of watermelon. *Plant Disease*, 102(7), 1394–1401.
- El-Moneim, D. A., Dawood, M. F., Moursi, Y. S., Farghaly, A. A., Afifi, M., & Sallam, A. (2021). Positive and negative effects of nanoparticles on agricultural crops. *Nanotechnology For Environmental Engineering*, 6(2), 21.
- El-Shafeey, E. S. I., Ghareeb, R. Y., Abd-Elhady, M. A., Abd-Elhady, S. H., & Salem, M. S. (2021). Defense-related genes induced by application of silver nanoparticles, ascorbic acid and salicylic acid for enhancing the immune response system of eggplant against invasion of root-knot nematode, *Meloidogyne javanica*. *Biotechnology & Biotechnological Equipment*, 35(1), 917–933.
- Fabiyyi, O. A. (2021). Sustainable management of *Meloidogyne incognita* infecting carrot (*Daucus carota*): Green synthesis of silver nanoparticles with *Cnidioscolus aconitifolius*. *Vegetos*, 34(2), 277–285.
- Fabiyyi, O. A., Atolani, O., & Olatunji, G. A. (2020a). Toxicity effect of *Eucalyptus globulus* on *Pratylenchus* spp. of *Zea mays*. *Sarhad Journal of Agriculture*, 36(4), 1244–1253.
- Fabiyyi, O. A., Alabi, R. O., & Ansari, R. A. (2020b). Nanoparticles' synthesis and their application in the management of phytonematodes: An overview. In *Management of phytonematodes: Recent advances and future challenges* (pp. 125–140). Springer.
- Galadima, I. B. (2015). Enhanced nematicidal effect of cowdung soil amendment by neem (*Azadirachta indica*). *Open Access Library Journal*, 2(08), 1.
- Gamalero, E., & Glick, B. R. (2020). The use of plant growth-promoting bacteria to prevent nematode damage to plants. *Biology*, 9(11), 381.
- Ghareeb, R. Y., Shams El-Din, N. G. E. D., Maghraby, D. M. E., Ibrahim, D. S., Abdel-Megeed, A., & Abdelsalam, N. R. (2022). Nematicidal activity of seaweed-synthesized silver nanoparticles and extracts against *Meloidogyne incognita* on tomato plants. *Scientific Reports*, 12(1), 3841.
- Ghosh, V., Mukherjee, A., & Chandrasekaran, N. (2014). Eugenol-loaded antimicrobial nanoemulsion preserves fruit juice against microbial spoilage. *Colloids and Surfaces B: Biointerfaces*, 114, 392–397.
- Giannousi, K., Avramidis, I., & Dendrinou-Samara, C. (2013). Synthesis, characterization and evaluation of copper based nanoparticles as agrochemicals against *Phytophthora infestans*. *RSC Advances*, 3(44), 21743–21752.
- Gupta, S., Kushwah, T., Vishwakarma, A., & Yadav, S. (2015). Optimization of ZnO-NPs to investigate their safe application by assessing their effect on soil nematode *Caenorhabditis elegans*. *Nanoscale Research Letters*, 10(1), 303.
- Gupta, A., Singh, U. B., Sahu, P. K., Paul, S., Kumar, A., Malviya, D., et al. (2022). Linking soil microbial diversity to modern agriculture practices: A review. *International Journal of Environmental Research and Public Health*, 19(5), 3141.
- Haegeman, A., Vanholme, B., & Gheysen, G. (2009). Characterization of a putative endoxylanase in the migratory plant-parasitic nematode *Radopholus similis*. *Molecular Plant Pathology*, 10(3), 389–401.

- Haque, Z., & Khan, M. R. (2021). *Handbook of invasive plant-parasitic nematodes: Novel ingredients for use in pet, aquaculture and livestock diets*. CABI.
- Hassan, M. E., Zawam, H. S., El-Nahas, S. E., & Desoukey, A. F. (2016a). Comparison study between silver nanoparticles and two nematicides against *Meloidogyne incognita* on tomato seedlings. *Plant Pathology Journal (Faisalabad)*, 15(4), 144–151.
- Hassan, M. E. M., Zawam, H. S., Nahas, S. E. M. E., & Desoukey, A. F. (2016b). Comparison study between silver nanoparticles and two nematicides against *Meloidogyne incognita* on tomato seedlings. *Plant Pathology Journal (Faisalabad)*, 15(4), 144–151. <https://doi.org/10.3923/ppj.2016.144.151>
- Hockland, S., Niere, B., Grenier, E., Blok, V., Phillips, M., Den Nijs, L., et al. (2012). An evaluation of the implications of virulence in non-European populations of *Globodera pallida* and *G. rostochiensis* for potato cultivation in Europe. *Nematology*, 14(1), 1–13.
- Hudie, S., Pan, Z., Deliang, P., Wenkun, H., Ling-an, K., Chuanren, L., Enliang, L., & Huan, P. (2023). Current advances in the identification of plant nematode diseases: From lab assays to in-field diagnostics. *Frontiers in Plant Science*, 14, 1106784. <https://doi.org/10.3389/fpls.2023.1106784>
- Jaouannet, M., Magliano, M., Arguel, M. J., Gourgues, M., Evangelisti, E., Abad, P., & Rosso, M. N. (2013). The root-knot nematode calreticulin Mi-CRT is a key effector in plant defense suppression. *Molecular Plant-Microbe Interactions*, 26(1), 97–105.
- Jena, R., Das, M., Chattopadhyay, A., Patra, M., Temuhi, S., Tiwari, R. K., Lal, M. K., Kumar, R., & Behera, S. K. (2024). *Nanotechnology: An exciting perspective for nematode management; the nanotechnology driven agriculture* (1st ed., pp. 1–22). CRC Press.
- Kalaiselvi, D., Sundararaj, P., Premasudha, P., & Hafez, S. L. (2017). Nematicidal activity of green synthesized silver nanoparticles using plant extracts against root-knot nematode *Meloidogyne incognita*. *International Journal of Nematology*, 27(1), 81–94.
- Kausar, S. (2022). Application of copper-based nanomaterials against parasitic nematodes. In *Copper nanostructures: Next-generation of agrochemicals for sustainable agroecosystems* (pp. 263–290). Elsevier.
- Keating, B. A., Carberry, P. S., Bindraban, P. S., Asseng, S., Meinke, H., & Dixon, J. (2010). Eco-efficient agriculture: Concepts, challenges, and opportunities. *Crop Science*, 50, S-109.
- Khan, M. R., Fromm, K. M., Rizvi, T. F., Giese, B., Ahamad, F., Turner, R. J., et al. (2020). Metal nanoparticle–microbe interactions: Synthesis and antimicrobial effects. *Particle & Particle Systems Characterization*, 37(5), 1900419.
- Khan, M., Khan, A. U., Bogdanchikova, N., & Garibo, D. (2021). Antibacterial and antifungal studies of biosynthesized silver nanoparticles against plant parasitic nematode *Meloidogyne incognita*, plant pathogens *Ralstonia solanacearum* and *fusarium oxysporum*. *Molecules*, 26(9), 2462.
- Kostyukovsky, M., Rafaeli, A., Gileadi, C., Demchenko, N., & Shaaya, E. (2002). Activation of octopaminergic receptors by essential oil constituents isolated from aromatic plants: Possible mode of action against insect pests. *Pest Management Science*, 58(11), 1101–1106.
- Liang, W., Yu, A., Wang, G., Zheng, F., Jia, J., & Xu, H. (2018). Chitosan-based nanoparticles of avermectin to control pine wood nematodes. *International Journal of Biological Macromolecules*, 112, 258–263.
- Mahmood, A., Moosa, A., Khan, A. U. R., Maqsood, A., Kiani, B., Abbas, C., et al. (2024). Using essential oils to protect peaches from post-harvest rot caused by *Rhizopus* species. *Food*, 13(17), 2669.
- Maier, T. R., Hewezi, T., Peng, J., & Baum, T. J. (2013). Isolation of whole esophageal gland cells from plant-parasitic nematodes for transcriptome analyses and effector identification. *Molecular Plant-Microbe Interactions*, 26(1), 31–35.
- Malandrakis, A. A., Kavroulakis, N., & Chrysikopoulos, C. V. (2019). Use of copper, silver and zinc nanoparticles against foliar and soil-borne plant pathogens. *Science of the Total Environment*, 670, 292–299.

- McCarter, J. P., Dautova Mitreva, M., Martin, J., Dante, M., Wylie, T., Rao, U., et al. (2003). Analysis and functional classification of transcripts from the nematode *Meloidogyne incognita*. *Genome Biology*, 4, 1–19.
- Migunova, V. D., & Sasanelli, N. (2021). Bacteria as biocontrol tool against phytoparasitic nematodes. *Plants*, 10(2), 389.
- Mohamed, E. A., Elsharabasy, S. F., & Abdulsamad, D. (2019). Evaluation of in vitro nematocidal efficiency of copper nanoparticles against root-knot nematode *Meloidogyne incognita*. *South Asian Journal of Parasitology*, 2(1), 1–6.
- Mokrini, F., Janati, S., Houari, A., Essarioui, A., Bouharroud, R., & Mimouni, A. (2018). Management of plant parasitic nematodes by means of organic amendment. *Revue Marocaine des Sciences Agronomiques et Vétérinaires*, 6(3), 337–344.
- Mosa, M. A., & Youssef, K. (2021). Topical delivery of host induced RNAi silencing by layered double hydroxide nanosheets: An efficient tool to decipher pathogenicity gene function of Fusarium crown and root rot in tomato. *Physiological and Molecular Plant Pathology*, 115, 101684.
- Mukhtar, T., Kayani, M. Z., & Hussain, M. A. (2013). Response of selected cucumber cultivars to *Meloidogyne incognita*. *Crop Protection*, 44, 13–17.
- Nassar, A. M. K. (2016a). Effectiveness of silver nano-particles of extracts of *Urtica urens* (Urticaceae) against root-knot nematode *Meloidogyne incognita*. *Asian Journal of Nematology*, 5(1), 14–19. <https://doi.org/10.3923/ajn.2016.14.19>
- Nassar, A. M. K. (2016b). Research article effectiveness of silver nano-particles of extracts of *Urtica urens* (Urticaceae) against root-knot nematode *Meloidogyne incognita*. *Asian Journal of Nematology*, 5, 14–19.
- Nicol, J. M., Turner, S. J., Coyne, D. L., Nijs, L. D., Hockland, S., & Maafi, Z. T. (2011). Current nematode threats to world agriculture. In *Genomics and molecular genetics of plant-nematode interactions* (pp. 21–43). Springer.
- Ornat, C., Verdejo-Lucas, S., & Sorribas, F. J. (2001). A population of *Meloidogyne javanica* in Spain virulent to the Mi resistance gene in tomato. *Plant Disease*, 85(3), 271–276.
- Perry, R. N., & Moens, M. (2011). Introduction to plant-parasitic nematodes; modes of parasitism. In *Genomics and molecular genetics of plant-nematode interactions* (pp. 3–20). Springer.
- Prasad, T. N. V. K. V., Sudhakar, P., Sreenivasulu, Y., Latha, P., Munaswamy, V., Reddy, K. R., et al. (2012). Effect of nanoscale zinc oxide particles on the germination, growth and yield of peanut. *Journal of Plant Nutrition*, 35(6), 905–927.
- Raymaekers, K., Ponet, L., Holtappels, D., Berckmans, B., & Cammue, B. P. (2020). Screening for novel biocontrol agents applicable in plant disease management—a review. *Biological Control*, 144, 104240.
- Richards, R. M. (1981). Antimicrobial action of silver nitrate. *Microbios*, 31(124), 83–91; PMID 6799750.
- Roh, J. Y., Sim, S. J., Yi, J., Park, K., Chung, K. H., Ryu, D. Y., & Choi, J. (2009). Ecotoxicity of silver nanoparticles on the soil nematode *Caenorhabditis elegans* using functional ecotoxicogenomics. *Environmental Science & Technology*, 43(10), 3933–3940.
- Roskopf, E., Di Gioia, F., Hong, J. C., Pisani, C., & Kokalis-Burelle, N. (2020). Organic amendments for pathogen and nematode control. *Annual Review of Phytopathology*, 58, 277–311.
- Rupak, J., Manoranjan, D., Chattopadhyay, A., Mukesh, P., Temuhi, S., Tiwari, R. K., Lal, M. K., Kumar, R., & Behera, S. K. (2024). Nanotechnology: An exciting perspective for nematode management. In S. Roy & A. Hossain (Eds.), *The nanotechnology driven agriculture: The future ahead* (1st ed.). CRC Press. <https://doi.org/10.1201/9781003376446>
- Saad, A. M., Salem, H. M., El-Tahan, A. M., El-Saadony, M. T., Alotaibi, S. S., El-Shehawi, A. M., et al. (2022). Biological control: An effective approach against nematodes using black pepper plants (*Piper nigrum* L.). *Saudi Journal of Biological Sciences*, 29(4), 2047–2055.

- Sabry, A. K. H. (2019). Role of nanotechnology applications in plant-parasitic nematode control. In K. Abd-Elsalam & R. Prasad (Eds.), *Nanobiotechnology applications in plant protection. Nanotechnology in the life sciences*. Springer. https://doi.org/10.1007/978-3-030-13296-5_12
- Safeena, M. I. S., & Zakeel, M. C. M. (2020). Nanobiotechnology-driven management of phytonematodes. In R. Ansari, R. Rizvi, & I. Mahmood (Eds.), *Management of phytonematodes: Recent advances and future challenges*. Springer. https://doi.org/10.1007/978-981-15-4087-5_1
- Sardella, D., Gatt, R., & Valdramidis, V. P. (2017). Physiological effects and mode of action of ZnO nanoparticles against postharvest fungal contaminants. *Food Research International*, 101, 274–279.
- Sávoly, Z., Hrács, K., Pemmer, B., Streli, C., Záray, G., & Nagy, P. I. (2016). Uptake and toxicity of nano-ZnO in the plant-feeding nematode, *Xiphinema vuittenezi*: The role of dissolved zinc and nanoparticle-specific effects. *Environmental Science and Pollution Research*, 23, 9669–9678.
- Shahid, S., & Khan, M. R. (2019). Evaluation of biocontrol agents for the management of root-rot of mung bean caused by *Macrophomina phaseolina*. *Indian Phytopathology*, 72, 89–98.
- Siddiqui, Z. A., Parveen, A., Ahmad, L., & Hashem, A. (2019). Effects of graphene oxide and zinc oxide nanoparticles on growth, chlorophyll, carotenoids, proline contents and diseases of carrot. *Scientia Horticulturae*, 249, 374–382.
- Tamayo, L. A., Zapata, P. A., Vejar, N. D., Azócar, M. I., Gulppi, M. A., Zhou, X., et al. (2014). Release of silver and copper nanoparticles from polyethylene nanocomposites and their penetration into *Listeria monocytogenes*. *Materials Science & Engineering. C, Materials for Biological Applications*, 40, 24–31. <https://doi.org/10.1016/j.msec.2014.03.037>
- Thakur, R. K., Dhirta, B., & Shirkot, P. (2018). Studies on effect of gold nanoparticles on *Meloidogyne incognita* and tomato plants growth and development. *bioRxiv*, 1, 428144.
- Tiwari, R., Gupta, R. P., Singh, V. K., Kumar, A., Madhukar, P., Sundar, S., Gautam, V., & Kumar, R. (2023). *ACS Omega*, 8(45), 42014–42027. <https://doi.org/10.1021/acsomega.3c04587>
- Turnbull, C., Lillemo, M., & Hvoslef-Eide, T. A. (2021). Global regulation of genetically modified crops amid the gene edited crop boom—a review. *Frontiers in Plant Science*, 12, 630396.
- Vovlas, N., Troccoli, A., Palomares-Rius, J. E., De Luca, F., Liébanas, G., Landa, B. B., et al. (2011). *Ditylenchus gigas* n. sp. parasitizing broad bean: A new stem nematode singled out from the *Ditylenchus dipsaci* species complex using a polyphasic approach with molecular phylogeny. *Plant Pathology*, 60(4), 762–775.
- Weerasinghe, R. R. (2004). *Rhizobial-legume symbiosis and root knot nematode parasitism: Common signal transduction pathways in legumes*. North Carolina State University.

Part II

Applications

Chapter 5

Recent Advances of Nanobiotechnology in Plant Disease Management



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Abstract Manipulating atoms and molecules to make materials with incredibly small dimensions, such as nanoparticles that range in size from 1 to 100 nm, is the exciting topic of nanotechnology. Despite being relatively young, nanoscience and nanotechnology are developing quickly and continuously producing new findings. About 20–40% of crop losses occur each year as a result of certain pests as well as diseases. Currently, toxic pesticides are the main tool used to control plant diseases, and they are very toxic for environment. Nanotechnology, by using variously synthesized nanoparticles, presents a promising answer to these problems. These nanoparticles can be used as a useful tool to transfer genetic material to plants, possibly producing crops that are resistant to illness, and are also useful in controlling plant diseases. The review emphasizes the various ways that nanoparticles can improve crop resilience to disease as well as their ability to act as genetic material carriers. Nanoparticles have been utilized as bio-agents to many plant pathogens (virus, fungi and bacteria) and are directly used to manage infections. The review investigates the ways in which nanoparticles can improve plant resistance to stressors and increase plant responses to pathogen attacks. Along with summarizing recent developments in the implementation of nanomaterials for disease treatment and plant health monitoring, it also addresses the methods by which plant diseases are opposed by nanoparticles. The article also discusses the function of nanosensors in observation of plant health and the way in which nanoparticles might boost plant immunity by triggering a variety of defense processes.

Keywords Nanoparticles · Pathogen management · Nanoscience · Plant immunity · Defense mechanisms and nanosensors

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5.1 Introduction

Agriculture is vital to human growth since it generates food and revenue for many countries. The primary source of livelihood is agriculture where it represents about 86% of those living in rural areas (Chen & Yada, 2011). There is an urgent need for sustainable agricultural intensification since the world's crop consumption is predicted to increase everyday (Kutawa et al., 2021). This perspective is alarming since a multitude of biotic and abiotic elements combine to produce agricultural yield. However, disease in plants caused by biotic pressures (like pests and pathogens), abiotic stresses (like cold, drought, flooding, etc.), and nutrient deficiencies are the main reasons of low crop production and poor crop quality (Wang et al., 2016). Given that crops are the main source of income for a prosperous and sustainable society, crop production must rise to satisfy the needs of the world's ever growing population. An estimated (20–40%) of global yield productivity is lost annually due to pests and diseases (Panpatte & Jhala, 2019). These days, a wide range of chemicals are used for pest control, such as fungicides, insecticides, and pesticides. Additionally, estimates (Flood, 2010) indicate that the volatilization, evaporation, photolysis, and degradation of pesticides and fertilizers used to treat plant diseases lead to low usage and environmental damage.

In order to safeguard agricultural goods against illnesses both before and after harvest, pathogen management is essential. These illnesses, which are primarily caused by different plant pathogens are still difficult to prevent. Managing plant diseases most frequently involves using host-plant resistance. The process of conventional breeding depends on the existence of highly effective disease-resistant genes to develop improved plant populations over several generations (Shoala, 2021). The disadvantages of conventional breeding might be mitigated via transgenics. The insertion of foreign genes into transgenic plants provides persistent resistance to disease by making it less likely for pathogens to adapt (Sun et al., 2019). Despite their potential, the widespread benefits of genetically modified (GM) crops remain unrealized due to public apprehensions over safety and restrictive international regulations (Wally & Punja, 2010). The environmental consequences of heavy chemical pesticide use present another significant challenge. As a potential solution, nanotechnology is being increasingly employed. This field entails the engineering of materials at the atomic level to generate controlled, unique properties tailored for desired functions. A wide array of natural functions are also performed at the nanoscale. Consequently, the convergence of biological principles and nanotechnology offers a highly promising avenue for solving persistent problems and pioneering a revolution in agriculture (Gleiter, 2000). Material scientists have created nanoparticles with the required shapes, size, as well as surface properties. Through a variety of techniques, including conjugation, encapsulation, and adsorption, these particles can be employed as shields or for the targeted and exact dispersion of pesticides (Hamid & Saleem, 2022).

Present estimations of the world's population indicate that present agricultural production methods make achieving food security difficult. Conventional farming

dependent on agrochemicals has the additional negative consequences of severely reducing soil fertility and causing eutrophication. There is an immediate demand for cutting-edge technologies that can support higher output and crop protection. As an emerging tool, nanotechnology is increasingly being applied to revolutionize plant disease management through improved diagnostic and therapeutic techniques. Nanomaterials, which are paramount to nanotechnology, possess key attributes including a small size, extensive specific surface area, and significant surface activity. They also have the potential to overcome the drawbacks of earlier plant disease diagnosis and treatment techniques and usher in sustainable farming. Nanotechnology is the investigation of materials at the 1–100 nm scale, a size range where unique properties emerge, enabling innovative applications (US Environmental Protection Agency, 2007, as cited in Sangeetha et al., 2019). For the past two decades, a global initiative has been underway to advance scientific and technological research in agriculture and food systems, largely driven by the enabling potential of nanotechnology. Numerous economical agricultural applications are being developed with the help of nanoscience (Das et al., 2021). Indeed, numerous biotechnological applications of nanoparticles have been envisioned and explored, including (a) mitigating soil composition issues (Nair et al., 2010), restoring soil salinity, and stabilizing surfaces prone to erosion (Majeed & Taha, 2013); (b) improving how plants access nutrients (Mukhopadhyay, 2014); (c) analyzing soil conditions (Lisa et al., 2009); (d) create new agrochemicals like herbicides, insecticides, and pesticides (Ragaei & Sabry, 2014; De et al., 2014; Gan et al., 2010); and (e) tracking pollution (Deshpande et al., 2017). Biosensors, anti-microbial food packaging, nanomaterial-based barcoding, products that show the shelf life of agricultural products, the removal of contaminants and stubborn pesticides from soil and water and their bioremediation, and clay-based nano-constituents in water management are some more uses of nanotechnology in agriculture. In the last 10 years, antimicrobial nanoparticles have been used in agriculture increasingly often (Duhan et al., 2017). Given the critical role of agriculture in global food security, a thorough exploration of nanomaterials' applications is imperative. This research should focus on their use in diagnosing and controlling phytopathogens, as well as in genetically enhancing disease resistance. Furthermore, due to their demonstrated benefits in promoting development of vegetation and increasing tolerance to environmental stresses, nanomaterials hold significant promise for replacing conventional agrochemicals in crop cultivation. The food and agriculture industries could undergo a revolution thanks to nanoparticles' special ability to identify and control phytopathogens at the molecular level. Nanomaterials can be added to pesticides to prevent photodegradation and allow for a regulated pesticide release (Rico et al., 2015). Comparably, fluorescent markers for cellular imaging could be produced using semiconductor particles like quantum dots (Wang et al., 2016). Previous studies suggest that nanoparticles present a viable strategy for addressing the increasing issue of bacterial and fungal resistance to traditional antimicrobial agents (Kim et al., 2018). Consequently, a diverse array of nanomaterials—including metallic and non-metallic particles, polymers, carbon nanotubes (CNTs), and quantum dots—are now under

extensive investigation to evaluate their efficacy and potential uses in this field. Advanced applications of nanomaterials in health research have been successfully duplicated in plants (Siddiqui et al., 2015).

5.2 Nanoparticles as Protectants

Indeed, the advancement of agricultural nanotechnology is expected to greatly accelerate the development of insecticides and other active agents used in plant disease control. Plants can receive nanoparticle treatments in two main ways: either the nanoparticles are applied on their own to protect the crop, or they are used as carriers for other substances. These applications are done by spraying on leaves, soaking seeds, or through root uptake. The utilization of nanoparticles as delivery systems offers significant advantages for agrochemical application. These benefits include enhancing the shelf life of active ingredients, reducing the need for environmentally harmful chemicals, improving the water solubility of pesticides, and ensuring more reliable uptake by the target phytopathogen (Khandelwal et al., 2016). Furthermore, as noted by Hayles et al. (2017), nanocarriers can increase the efficacy and environmental resilience of nanopesticides. This enhanced performance allows for a reduction in the frequency of applications, thereby lowering overall toxicity, environmental impact, and cost.

The unique properties of metal-based nanoparticles, such as zinc oxide, iron oxide, calcium phosphate, gold, and silver, are particularly valuable due to their stability, hydrophilic nature, biocompatibility, and low toxicity (Kurtjak et al., 2017). Their ability to combat microbes functions largely through the release of ions. These ions produce reactive oxygen species (ROS), which are lethal to pathogens upon ingestion. For instance, copper and zinc nanoparticles efficiently produce ROS, while silver and gold nanoparticles exhibit high toxicity to bacteria even at minimal concentrations. Additionally, these nanoparticles can directly disrupt pathogen cell membranes. The collective application of inorganic nanoparticles leads to the production of metal ions, free radicals, and ROS, providing a multifaceted approach to inhibiting and eliminating microbial threats. Furthermore, certain nanoparticles are capable of infiltrating cellular structures and interacting with genetic material. A well-established antimicrobial mechanism involves the binding of metal ions to functional groups on biological molecules; for instance, they can bind to amine ($-NH_2$) or thiol ($-SH$) moieties in proteins. This binding often leads to protein denaturation, deactivation, and precipitation, ultimately disrupting essential cellular processes and contributing to the nanoparticle's biocidal effect. Mittapally et al. (2018) claim that because proteins have a high affinity for metal ions, cellular concentrations grow, which eventually leads to cell death. The production of nanocapsules and nanospheres relies on polymeric nanoparticles (PNPs). According to Stanisic et al. (2018), a key advantage of PNPs is that they can be synthesized from a range of biodegradable and non-toxic polymers. Furthermore, a range of substances can be discharged under control by using nanoparticles as carriers for substances like

pheromones, drugs that result in systemic acquired resistance, active ingredients in pesticides, etc. Nanoparticles demonstrate significant antimicrobial efficacy against a broad spectrum of plant pathogens, including viruses, fungi, and bacteria. Their mechanism of action involves multiple pathways that disrupt pathogen cells, ultimately leading to cell death. Controlling these pathogens is crucial, as they are a primary factor limiting the production of food crops.

5.2.1 Antiviral

Plant viruses are a major threat to global food security, causing nearly half of all agricultural crop losses. To combat this, nanomaterials (NMs) have emerged as a highly promising solution. Their efficacy has been demonstrated against several economically devastating viruses, including potato virus Y (PVY), bean yellow mosaic virus (BYMV), and cucumber mosaic virus (CMV).

Nanoparticles function through two primary antiviral strategies: direct action and targeted delivery. Their direct virucidal mechanisms include generating reactive oxygen species (ROS) and inhibiting viral attachment to host cells. A key tactic involves nanoparticles binding to viral surface proteins via glycoprotein receptors, which masks the virus and prevents its entry into host cells. For example, zinc oxide (ZnONPs), iron oxide (Fe₃O₄NPs), and Schiff base-derived silver NPs have been shown to cause the aggregation and disintegration of Tobacco mosaic virus (TMV) particles, drastically reducing viral colonization and disease severity (Abdelkhalek & Al-Askar, 2020).

Perhaps more significantly, nanoparticles excel as sophisticated delivery platforms. A primary mechanism is their use in RNA interference (RNAi), where they act as nanocarriers to deliver nucleic acids. This approach preserves plant immunity and promotes sustained resistance (Warghane et al., 2024). Innovations like clay nanosheets delivering plasmid DNA for artificial microRNAs (amiRNAs) have conferred resistance to tomato yellow leaf curl virus (Liu et al., 2020). Similarly, BioClay technology, which uses layered double hydroxide nanoparticles to deliver RNAi molecules, provides prolonged protection against viruses by enhancing the stability and efficiency of the therapeutic payload (Mitter et al., 2017).

Thus, nanoparticles function not only as standalone protective agents but also as efficient, multi-functional systems for managing plant viral diseases. The antiviral action of metallic nanoparticles is multifaceted. Silver nanoparticles (AgNPs) induce systemic acquired resistance against pathogens like Potato virus Y and Tomato mosaic virus. Studies using transmission electron microscopy have visualized AgNPs binding to and coating viral coat proteins, thereby preventing infection (Hamid & Saleem, 2022). Gold nanoparticles (AuNPs) act as mechanical abrasives, with evidence suggesting they cause the dissolution of viral particles, granting the plant resistance (Alkubaisi et al., 2015). Furthermore, biopolymer-based nanoparticles such as chitosan exhibit broad-spectrum antiviral activity, protecting plants against Alfalfa, Snuff, Potato, Cucumber, and Peanut mosaic viruses by stimulating innate resistance in plant tissues (Chirkov, 2002).

5.2.2 *Antinematodal*

Positive results have been observed when plant parasitic nematodes are suppressed with nano-Ag. Numerous studies examining the effects of nano Ag on *Meloidogyne* species have shown that it is effective in completely inactivating all stages of juveniles of *Meloidogyne* spp. in a short amount of time, usually 6 h (Nassar, 2016). A notable field application demonstrating the efficacy of nanoscale silver (nano-Ag) involved the treatment of a commercial putting green infected with the nematode *Meloidogyne graminis*. The bi-weekly application of nano-Ag at a rate of 90.40 mg/m² resulted in a significant suppression of root gall formation and a marked improvement in the overall quality of the turfgrass (Cromwell et al., 2014). Furthermore, research has shown that low concentrations of nano-Ag can effectively suppress *M. javanica* and *M. incognita*, obtaining control levels comparable to those offered by traditional nematicides (Ardakani, 2013).

5.2.3 *Antifungal*

Extensive research has demonstrated the potent and broad-spectrum antifungal properties of various nanoparticles. Silver nanoparticles (AgNPs) have been shown to exhibit significant efficacy against a diverse range of fungi, including pathogenic yeasts such as *Candida albicans*, *C. krusei*, *C. tropicalis*, and *C. glabrata*, as well as the mold *Aspergillus brasiliensis* (Bryaskova et al., 2011). Their activity extends to major plant pathogens, with studies reporting suppression of *Rhizoctonia solani*, *Botrytis cinerea*, *Alternaria alternata*, *Macrophomina phaseolina*, *Sclerotinia sclerotiorum*, and *Curvularia lunata* (Krishnaraj et al., 2012). Zinc oxide nanoparticles (ZnONPs) also display strong fungicidal effects. They are effective against pathogens like *Penicillium expansum* and *B. cinerea*, primarily by inhibiting critical fungal developmental processes including the germination of conidia, the formation of conidiophores, and the elongation of hyphae. The morphology of the nanoparticles is a key factor in their efficacy; for instance, platelet-shaped ZnO particles have been observed to possess greater antifungal activity against *Fusarium solani* compared to rod-shaped or spherical nanoparticles (Pariona et al., 2020).

Chitosan-based nanoparticles represent another promising category of biogenic antifungals. Valued for their inherent antibacterial action, biodegradability, biocompatibility, and low toxicity to humans and animals, chitosan is an excellent material for formulating microparticles and nanoparticles (Zhou et al., 2011). Notably, the nano- or micro- formulation of chitosan significantly enhances its biological activity compared to its bulk solution form, making it a more effective agent for agricultural applications (Huang et al., 2009).

Indeed, the body of research confirms the broad-spectrum fungistatic activity of chitosan nanoparticles against a significant number of economically important fungal pathogens. As evidenced by the cited studies, their efficacy spans:

Storage and Food Spoilage Molds: Including *Aspergillus niger* (Martínez-Camacho et al., 2010) and *A. parasiticus* (Cota-Arriola et al., 2011).

Destructive Plant Pathogens: Such as *Alternaria alternata*, *Colletotrichum gloeosporioides*, *Botrytis cinerea*, and *Rhizopus stolonifer* (Bautista-Baños et al., 2006).

This established efficacy, combined with chitosan's inherent biodegradability and low toxicity, solidifies its role as a highly promising platform for developing sustainable, nano-enabled fungicides to protect crops both in the field and during post-harvest storage. The mechanism often involves inhibiting spore germination and mycelial growth, effectively suppressing disease progression.

Furthermore, it has been shown to have fungicidal effects on *Penicillium digitatum*, *R. stolonifer*, *C. gloeosporioides*, and *Fusarium oxysporum*. Cu/Cu₂O nanoparticles' antifungal efficacy against *F. oxysporum* was examined. The antifungal mechanism of these nanoparticles involves inducing structural and physiological damage to fungal cells. This includes generating reactive oxygen species (ROS), causing membrane integrity loss, altering hyphal morphology, and inhibiting radial growth (Hermida-Montero et al., 2019).

The efficacy of this approach is demonstrated in practical applications. For instance, metalloid and metal oxide nanoparticles have been successfully used to combat Fusarium wilt in watermelons. In a study by Elmer et al. (2018), a foliar spray application containing nanoparticles of boron (B), copper oxide (CuO), silicon oxide (SiO), manganese oxide (MnO), titanium oxide (TiO), and zinc oxide (ZnO) proved effective in managing the disease.

In summary, the evidence indicates that nanomaterials, particularly those based on silver, zinc oxide, and chitosan, offer a versatile and potent tool for managing fungal pathogens in agriculture, acting through multiple mechanisms of inhibition.

5.2.4 Antibacterial

Nanoparticles exhibit potent antimicrobial activity, primarily attributed to their distinct physicochemical characteristics such as their minute size, high surface area-to-volume ratio, and increased reactivity. For example, silver nanoparticles biologically synthesized from *Solanum trilobatum* and *Ocimum tenuiflorum* can suppress the growth of pathogenic bacteria including *Pseudomonas aeruginosa*, *Escherichia coli*, and *Klebsiella pneumoniae*. Zinc nanoparticles have also been shown to inhibit *P. aeruginosa* (Jayaseelan et al., 2012).

Furthermore, copper oxide (CuO) nanoparticles display broad-spectrum antibacterial properties effective against multiple bacterial species (Azam et al., 2012). Chitosan nanoparticles are another versatile category, demonstrating antimicrobial effects against bacteria (both Gram-negative and Gram-positive), viruses, and fungi. They have proven particularly effective against Gram-negative pathogens such as *E. coli*, *P. aeruginosa*, *Salmonella typhimurium*, *Pseudomonas fluorescens*, and *Vibrio parahaemolyticus* (Palma-Guerrero et al., 2010).

5.3 Mechanisms of Nanoparticle Action Against Plant Pathogens

Numerous situations have been connected to the toxicity of nanomaterials. Consuming free nano-ions disrupts DNA replication and ATP generation and directly damages the cellular membrane. It is simple to see the morphological changes that occur when unicellular organisms are exposed to millimolar concentrations of nano-ions. The antimicrobial action of nanoparticles (NPs) induces severe structural and functional alterations in bacterial cells. This damage culminates in the leakage of a cell's contents, following a series of changes that include the shrinkage of the cytoplasm and the condensation and misplacement of DNA (Elsharkawy & Derbalah, 2019). A key biochemical mechanism for this toxicity occurs at the metabolic level. A key mechanism involves the release of ions, which, even in trace amounts, can impair essential respiratory processes by inhibiting enzymes like NADH dehydrogenase. This interaction disrupts the electron transport chain, uncoupling respiration from adenosine triphosphate (ATP) synthesis. Consequently, the cell is unable to produce energy, leading to its death. Moreover, the attachment of transport proteins and ionic nanoparticles causes protons to leak out and the proton motive force to break down (Jung et al., 2008). Research indicates that nanoparticle absorption can induce genotoxicity, a phenomenon observed as DNA mutations both in PCR processes and in *Escherichia coli* cells (Özel et al., 2013). The broader toxicological profile of nanoparticles has been extensively studied across a wide range of biological models, including isolated cell lines, rats, aquatic species, algae, and immune cells such as macrophages (Miao et al., 2016).

5.3.1 Formation of Reactive Oxygen Species (ROS)

The principal mechanism of nanotoxicity is driven by the formation of reactive oxygen species (ROS) after nanoparticles are internalized by cells. This increase in ROS causes oxidative stress, resulting in DNA damage, disrupted cell signaling, changes in cell motility, cytotoxicity, and apoptosis (programmed cell death) (Miao et al., 2016). The amount of ROS generated depends strongly on the nanomaterial's chemical makeup (Carlson et al., 2008).

ROS are naturally produced during cellular oxidative metabolism, mainly in the mitochondria as a byproduct of ATP synthesis. Here, the electron transport chain reduces oxygen to water. Incomplete reduction leads to the formation of superoxide anion radicals, which can produce other highly reactive ROS such as hydrogen peroxide, hydroxyl radicals, and singlet oxygen. Among these, the hydroxyl radical is especially genotoxic, causing severe oxidative DNA damage such as: lesions to DNA bases and sugar moieties, abasic sites (loss of nitrogenous bases), Single-strand and double-strand breaks, and DNA-protein crosslinks (Fu et al., 2014).

Cells defend against ROS using antioxidant enzymes. Superoxide dismutase (SOD) converts superoxide into hydrogen peroxide and oxygen. Although superoxide is a mild oxidant, its conversion to hydrogen peroxide is critical because hydrogen peroxide can later form highly damaging hydroxyl radicals via the Fenton reaction. Subsequently, catalase and peroxidases break down hydrogen peroxide into water and oxygen (Valko et al., 2006). Nanoparticle-induced toxicity often occurs when these particles produce ROS at levels that overwhelm the cell's antioxidant defenses, resulting in irreversible oxidative damage and cell death.

5.3.2 Nanoparticle-Induced Cell Membrane Damage

A well-established pathway of nanotoxicity involves the direct physical and chemical disruption of cellular membranes by nanoparticles. Seminal work on quantum dots, for example, revealed their ability to induce direct membrane damage (Wardman & Candeias, 1996), a process often driven by oxidative mechanisms. Studies show that silica nanoparticles provoke dose-dependent cytotoxicity and oxidative stress, chiefly by generating reactive oxygen species (ROS) that initiate lipid peroxidation of the membrane (Akhtar et al., 2010). In a similar manner, copper oxide nanoparticles (nano-CuO) stimulate dose-dependent ROS production and lipid peroxidation, resulting in oxidative stress, cytotoxicity, and the leakage of lactate dehydrogenase (LDH)—a standard marker for loss of membrane integrity—in human alveolar epithelial cells. The exact process of nanoparticle internalization into bacterial cells remains incompletely understood across all species; a prominent model, however, highlights the role of electrostatic attraction. The typically negative charge of bacterial cell surfaces attracts positively charged nanoparticles (Raffi et al., 2008). This adhesion is frequently a crucial initial event that enables further physical disruption or localized ROS production, leading to a breach of membrane integrity.

5.3.3 Liberation of Toxic Components

A primary mechanism by which nanoparticles exert their antibacterial effect is through the leaching of toxic substances, such as heavy metal ions. A prominent example is the toxicity of silver nanoparticles (AgNPs), which is largely attributed to the release of silver ions (Ag^+). These ions inactivate essential microbial enzymes by binding to thiol ($-\text{SH}$) groups in proteins, disrupt DNA replication, and alter cell membrane permeability and structure (Hoseinnejad et al., 2018). Quantum Dots (QDs) represent another class of potent nanoparticles. Their structure typically consists of a core made from elements like cadmium-selenide (Cd-Se) or zinc-selenide (Zn-Se), encapsulated within a shell (e.g., ZnS or CdS) and coated with an organic polymer layer. Studies have demonstrated that bacteria like *E. coli* and *Bacillus subtilis* can internalize these QDs, leading to toxic effects (Adetunji &

Ugbenyen, 2019). The efficacy of nanoparticles as antimicrobial agents has been extensively validated using standard model organisms, including the bacterium *Staphylococcus aureus*, the yeast *Candida* species, and the gram-negative bacterium *E. coli* (Dizaj et al., 2014). Beyond direct antimicrobial activity, nanoparticles themselves are the active ingredients in advanced “nanopesticides” (Kah & Hofmann, 2014). Their suitability for this application stems from a unique set of physico-chemical properties—including enhanced solubility, permeability, thermal stability, crystallinity, and controlled biodegradability—which make them ideal components for formulating more effective and targeted pesticide delivery systems (Khezerlou et al., 2018). The very accurate surface area of these materials accounts for their higher affinity for the objective (Bouwmeester et al., 2009). By preparing agricultural formulations at the nanoscale, which improves their wet ability and dispersion, organic solvent flow-off and undesired pesticide migration are reduced (Kah & Hofmann, 2014). It has nanoscale distribution systems for insecticides and pesticides with controlled release characteristics (Yan et al., 2005). Because they are inexpensive, biodegradable, and non-toxic, natural polymers like cellulose, hemicellulose, gelatin, albumin, sodium alginate and chitosan can be used to make nanomaterials. Inorganic nanoparticles and conventional fungicides are both present in nanoformulations that have been studied for the purpose of controlling disease. According to Khan and Rizvi (2014), these formulations may improve agricultural productivity, decrease utilization of dangerous pesticides and their detrimental effects on the environment, and improve disease control. In order to reduce the amount of active ingredient in pesticides while maintaining performance and preventing pesticide losses from evaporation and leaching, nanomaterials must be incorporated into the formulation process. However, after an ecotoxicological assessment, field applications would require safety and regulatory permissions (Yearla & Padmasree, 2016). A recent study (Kumar et al., 2019) examined the use of nanomaterials as fertilisers, pesticide delivery agents, micronutrients, and insecticides.

5.4 Nanobiosensor Technologies for Plant Pathogen Detection

According to Romanovskii and Periakaruppan (Romanovski & Periakaruppan, 2023), nanocomposites of organic, inorganic, or mixed materials are what make up nanobiosensors. These materials are created via innovative nanotechnological techniques. Many nanomaterials, including metals, magnetic nanoparticles, carbon nanotubes (CNTs), nanowires, nano-probes, and quantum dots (QDs), are used in nanobiosensors (Fig. 5.1). Real-time crop condition monitoring utilizing piezoelectric nanosensors to measure moisture content, nutrients, pH, and temperature in the soil is one use of nanobiosensors in agriculture (Dimri et al., 2020). With the increasing acceptance of nanocomposites, agricultural crops can avoid using synthetic chemicals, fungicides, and pesticides to control plant pests. To guarantee the

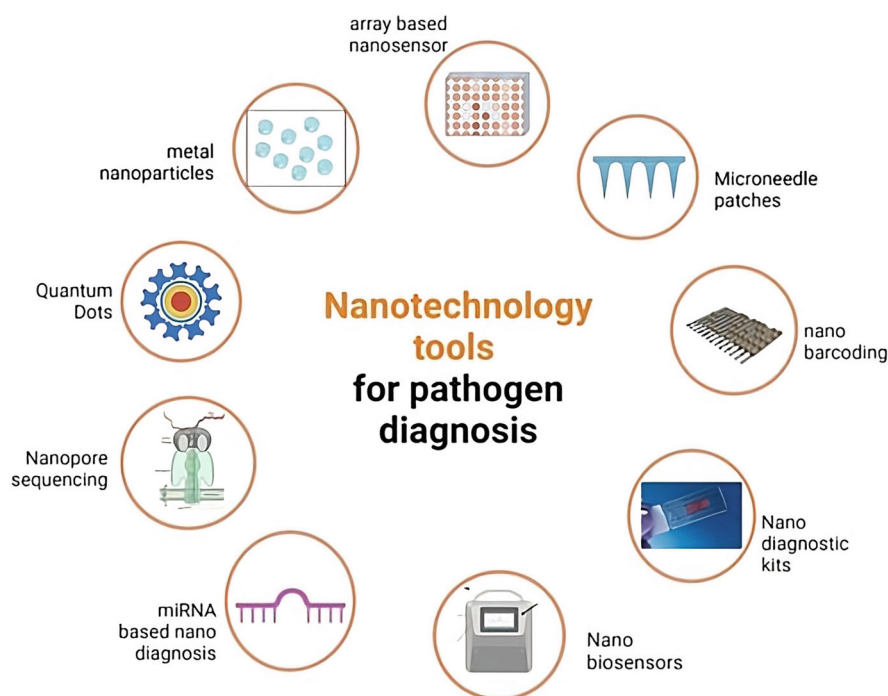


Fig. 5.1 Nanotechnology-based tools for the detection of phytopathogens (Ray et al., 2023)

effective transfer of nutrients through foliar or root treatments, small-scale nanocomposites get past biological barriers (Ijaz et al., 2023).

A recent innovation in nanotechnology is the development of nanosensors—biosensors that incorporate nanoparticles. These devices hold transformative potential for the agri-food sector. Their value stems from a combination of highly desirable characteristics, including their small size, portability, high efficiency, and exceptional sensitivity and specificity. Originally advanced by researchers in clinical diagnostics and scientific institutions, these nanoparticle-based biosensors are now poised to revolutionize agriculture and food science. Their applications are multifaceted, including extending fruit shelf life, enhancing the health profile of oils, protecting plants from disease, promoting more sustainable agricultural practices, and enabling miniaturized, efficient delivery systems for agrochemicals (Dar et al., 2020). Farmers can detect plant diseases early on thanks to the availability of nanobiosensor-detection devices, which helps them avoid suffering large financial losses. Modern biosensing methods, such the use of nanosensors, enable earlier infestation management, which lowers production losses. Accurate detection of these illnesses can help in the development of plant treatments (Ali et al., 2021). These advanced diagnostic methods are sometimes known as “nano-diagnostics.” Nanobiosensors have been used to identify contaminating pathogens. Gold

nanoparticles (AuNPs) serve as a versatile platform for advanced phytopathogen detection. A significant application is the development of gold-based nanobiosensors designed to identify both plant diseases and agro-terrorism agents, such as toxic chemicals (Acharya & Pal, 2020). The efficacy of these DNA-based detection methods relies on a critical step: the rhythmic, ordered formation of pathogen-specific DNA segments during recombinase polymerase amplification (RPA), which is subsequently analyzed via electrodeposition. This process ensures high specificity in identifying the target pathogen. Complementing these methods, alternative sensing strategies have been developed. For instance, Vaseghi et al. (2013) proposed a colorimetric technique utilizing gold nanoparticles for the visual detection of *Pseudomonas syringae*, demonstrating the broad utility of AuNPs in creating rapid, on-site diagnostic tools. A similar colorimetric technique was used to identify the pathogen responsible for potato wilt disease, *Ralstonia solanacearum*. This assay did not require previous DNA amplification; rather, the presence of the microbe was ascertained directly through interaction with a representative sample of topsoil (Ha et al., 2018).

5.4.1 Plant Pathogen Detection Using Nanomaterial-Based Biosensors

Two types of electrochemical biosensors are distinguished by their biocatalytic and biocomplexing biorecognition components. In biochemical sensing applications, enzymes are commonly employed as biorecognition components; however, they are typically employed as labels in the secondary binding stage of pathogen detection (Choi et al., 2018). This is how organized molecular assemblages trigger a biosensor's response, or how analytes interact with macromolecules. A variety of factors—including test design, sample volume, material properties, the characteristics of the pathogen-containing sample, and the specific application—collectively influence this procedure and determine the optimal measurement format (Jeeranpan et al., 2020).

Indeed, nanotechnology has facilitated the creation of advanced biosensing platforms that offer exceptional sensitivity for the rapid and precise detection of plant pathogens. Among these, electrochemical methods—such as impedimetric, amperometric, potentiometric, and conductimetric techniques—utilize functionalized electrodes to detect electrical changes resulting from pathogen binding. These approaches can achieve detection limits as low as a few viral particles or picograms per milliliter, demonstrating sensitivity comparable to PCR (Saxena et al., 2018; Chen et al., 2016). Complementing these electrochemical methods, optical biosensors—including surface plasmon resonance (SPR), fluorescence-based assays, and colorimetric sensors—generate visible or light-based signals that enable user-friendly, field-deployable diagnostic tools (Umapathi et al., 2022). Together, these nano-enabled sensors support early and precise pathogen identification,

contributing to more sustainable crop protection and reduced agricultural losses. By searching for a change in color, colorimetric biosensors may detect harmful bacteria in samples in 10–15 min. Both a solution-based and a flat-based approach can be used to perform the test. In order to describe hyperspectral reflectance signals across the pathogenesis of brown rust, powdery mildew, and net blotch in barley, Wahabzada et al. (2016) developed a machine-learning technique. This might lead to the developing for creating a new type of spectral library that uses spectral properties to represent plant health and diseases. In addition to providing a number of advantages, hyperspectral signature collecting of plants would allow non-experts to enter this sector.

Recent advances in nanosensor design have significantly improved the detection of plant pathogens through highly specific and sensitive platforms. For instance, Yazgan et al. (2018, 2021) developed a lectin-based biosensor using glycoconjugate-functionalized gold nanoparticles to detect *Penicillium italicum* in fruit, achieving exceptional sensitivity (4×10^2 spores/mL) and selectivity against related fungi like *Aspergillus nidulans* and *Colletotrichum gloeosporioides*, with specificity attributed to sugar ligands rather than nanoparticle morphology. Similarly, Yao et al. (2009) employed antibody-conjugated fluorescent silica nanoparticles to identify *Xanthomonas axonopodis* pv. *vesicatoria*, while Firrao et al. (2005) utilized fluorescent DNA oligonucleotides on gold nanoparticles to detect Flavescence dorée phytoplasma in grapevines. These studies underscore the utility of functionalized nanoparticles in enabling early, accurate, and field-deployable diagnostics for agriculturally critical diseases. Furthermore, research has demonstrated the application of specific nanosensors for detecting various agricultural pathogens and toxins. For instance, an electrochemical sensor utilizing gold nanoparticles successfully identified *Pseudomonas syringae* in *A. thaliana* plants using differential pulse voltammetry (Lau et al., 2017). In the realm of food safety, nanosensors like the competitive antibody-based 4mycosensor have been developed to detect major mycotoxins—including ZEA (zearalenone), T-2/HT-2 toxins, DON (deoxynivalenol), and fumonisins (FB1/FB2)—in key cereals such as maize, wheat, oats, and barley (Lattanzio & Nivarlet, 2017). Additionally, quantum dot (QD)-based biosensors have shown significant promise for viral pathogen detection. These have been effectively employed to identify a range of economically important plant viruses, such as: Cauliflower mosaic virus (Sun et al., 2008), Citrus tristeza virus (Shojaei et al., 2016), Arabis mosaic virus (Zhang et al., 2013), and Cowpea mosaic virus (Medintz et al., 2005).

5.5 Enhancing Plant Immunity

Novel strategies to improve plant tolerance are needed to ensure agricultural yield under stress. Crop improvement and disease resistance have benefited greatly from conventional breeding, which capitalizes on natural variation (Rodriguez-Moreno et al., 2017). But when faced with difficult problems like particular insect resistance

or environment adaption that changes quickly, its efficacy wanes. Reliance on genetic diversity, imprecise results, limited precision and resource-intensive procedures with an impact on the environment is some of the limitations (Tiwari et al., 2022). Genetic engineering, genome editing, and TILLING are examples of genomic breeding approaches that exhibit promise but are hampered by technical difficulties, lack of farmer accessibility, and regulatory issues (Gao, 2021; Koseoglou et al., 2022). Significant obstacles also include possible unintended repercussions and public opposition in some areas (Gonzalez Guzman et al., 2022).

Indeed, the rapid advancement of nanotechnology has established it as a pivotal innovation in modern agriculture, offering transformative solutions to critical challenges such as biotic and abiotic stressors. By supporting more sustainable and climate-resilient farming systems, nanotechnology contributes significantly to enhanced crop resilience, yield stability, and resource efficiency (Zain et al., 2023). Its applications are wide-ranging and include:

- Targeted agrochemical delivery: Nano-enabled systems improve the precision and efficiency of pesticides and fertilizers, reducing environmental leakage and increasing uptake.
- Soil health enhancement: Nanomaterials can remediate degraded soils, improve water retention, and support beneficial microbial communities.
- Advanced pathogen detection: Nanosensors allow for rapid, sensitive, and field-deployable diagnosis of plant diseases, enabling early intervention.

These innovations collectively promote a more productive, ecological, and resilient agricultural system.

A particularly promising application lies in plant defense priming, where nanoparticles (NPs) play a critical role. When plants are pre-treated with NPs, they undergo a state of heightened alertness, enabling faster and more robust responses to subsequent stressors such as pathogens, droughts, or extreme temperatures. This priming effect not only enhances crop resilience but also decreases the need for conventional chemical inputs, aligning with sustainability goals (Zhao et al., 2020). As research progresses, nanotechnology is poised to revolutionize agricultural systems, making them more efficient, adaptive, and environmentally friendly. Through this process, plants are able to respond to secondary stimuli more quickly and efficiently, which enhances total plant performance. Plant physiology, morphology, and growth have all been shown to be influenced by NPs (Nile et al., 2022). Nanoparticles play a significant role in boosting plant resilience to stress by influencing key physiological and biochemical processes. They modulate the activity of enzymes involved in reactive oxygen species (ROS) production and the antioxidant system—including peroxidase (POD), superoxide dismutase (SOD), and catalase (CAT). At the same time, nanoparticles enhance critical leaf components such as protein and chlorophyll content, as well as total phenolic compounds (TPC). These changes collectively improve plant defense mechanisms and metabolic performance under stressful conditions (Shafiq et al., 2019).

Recent progress in nanotechnology has enabled the design of tailored nanoparticles (NPs) for targeted crop protection (Yang et al., 2022). A particularly

promising strategy is defense priming, in which the application of NPs enhances a plant's innate immunological memory and strengthens its resistance to disease. For instance, mycogenic selenium nanoparticles (SeNPs) applied to tomato seeds promoted the accumulation of lignin and hydrogen peroxide and upregulated key defense-related genes—including those encoding lysyl oxidase (LOX), glucanase (GLU), phenylalanine ammonia-lyase (PAL), and superoxide dismutase (SOD). This primed immune response provided strong protection against *Phytophthora infestans*, the causal agent of late blight, across various developmental stages (Joshi et al., 2021). In pearl millet, SeNPs synthesized using *Trichoderma* spp. suppressed both growth and sporulation of *Sclerospora graminicola*, the downy mildew pathogen. When used in combination with *T. asperellum*, these nanoparticles not only reduced disease incidence but also enhanced plant growth under greenhouse conditions (Nandini et al., 2017). These examples highlight how nanotechnology—particularly when paired with biological agents—can offer sustainable, efficient, and scalable solutions for seed treatment and integrated crop protection.

AgNP-primed seeds shown notable improvements over hydroprimed seeds, including quicker germination, increased seedling vigor, higher biomass, and notably longer roots, according to Yan et al. (2022). However, multiomics analyses involving metabolomics and transcriptomics demonstrated that AgNPs priming caused significant metabolic and transcriptional changes in rice seeds, as evidenced by a notable increase in signaling metabolites such as niacinamide, salicylic acid, and glycerol-3-phosphate following AgNPs priming. Research by Yan et al. (2022) demonstrates that treating seeds with silver nanoparticles (AgNPs) activates critical biochemical defense pathways in plants. These include systems responsible for hormone signaling, glutathione metabolism, and the production of defensive compounds like flavones and flavonols. This priming effect essentially “tunes” the plant's immune system, leading to a state of enhanced readiness. Remarkably, this induced resistance, termed “stress memory” by the authors, persists for weeks, equipping rice seedlings with prolonged protection against diverse threats like cold, salt stress, and fungal infection by *Magnaporthe oryzae* (Yan et al., 2022).

Furthermore, Yan et al. (2022) found that this robust defense activation is transgenerational. The offspring of primed plants exhibit stronger growth and higher germination rates, suggesting a powerful epigenetic strategy for crop improvement that could reduce reliance on chemical pesticides and bolster sustainable agriculture. In a parallel study on maize, Xiao et al. (2023) found that applying silicon quantum nanodots (SiNDs) to soil similarly boosted the plant's innate defenses against armyworm caterpillars (*Mythimna separata*). The treatment was shown to enhance both physical barriers through increased lignin deposition and chemical defenses via the production of benzoxazinoids (Xiao et al., 2023). Additionally, the researchers reported that SiNDs amplified the plant's antioxidant response during infestation by upregulating protective enzymes and flavonoids.

A study by Narasimhamurthy et al. (Narasimhamurthy et al., 2022) demonstrated that tomato plants primed with chitosan nanoparticles (CNPs) demonstrated a strong correlation between enhanced activity of antioxidant enzymes and the increased

expression of their corresponding genes, highlighting a coordinated molecular and biochemical response in primed plants that was absent in non-primed controls. This consistent gene-to-phenotype alignment underscores the role of nanoparticles in activating robust, multilevel defense mechanisms. This indicates that CNPs initiate a multifaceted defense response in tomato plants, encompassing cellular, biochemical, and genetic levels. These coordinated reactions effectively promoted plant growth and yield while conferring robust resistance against bacterial wilt disease (Narasimhamurthy et al., 2022). The induced resistance mechanisms observed by Narasimhamurthy et al. (2022) included heightened deposits of lignin, callose, and hydrogen peroxide (H_2O_2) an accumulation of superoxide radicals in leaf tissues, and a significant overexpression of key defense-related enzymes such as peroxidase (POD), phenylalanine ammonia-lyase (PAL), β -1,3-glucanase (GLU), catalase (CAT), and polyphenol oxidase (PPO). Extending these promising greenhouse results to field conditions, recent research further demonstrates the agronomic benefits of nanoscale materials. In a complementary field study, Xiao et al. (2023) reported that the application of silicon quantum nanodots (SiNDs) significantly enhanced maize productivity, resulting in increased 100-grain weight, cob weight, and overall grain yield.

5.6 Nanoparticles Activate Plant Defense mechanisms Through Different Way

Plant defense mechanisms can be activated by nanoparticles through a variety of paths. Together, these systems enable plants to more effectively tolerate and overcome a range of stressors, enhancing their resilience and general health.

5.6.1 Antioxidant System

Indeed, plants employ reactive oxygen species (ROS) as central signaling molecules in their immune response to both biotic and abiotic stressors. The controlled production of ROS acts to restrict pathogen spread and initiates critical defense cascades. These include the hypersensitive response (HR)—a form of programmed cell death at the infection site—and the activation of systemic acquired resistance (SAR), which primes the entire plant for future attacks.

However, maintaining ROS levels is critical. When their concentration exceeds a certain threshold, the delicate balance between ROS and antioxidants is disrupted, leading to the production of harmful oxidative products. To counteract this damage and mitigate the effects of these oxidants, plants rely on a sophisticated antioxidant defense system. An antioxidant system in plants lessens the impact of oxidants. The

antioxidant system includes enzymes such as guaiacol peroxidase (GPX), ascorbate peroxidase (APX), catalase (CAT), and superoxide dismutase (SOD) (Tan et al., 2018). This dual role of nanoparticles (NPs) in redox modulation is a key concept. As highlighted by Soares et al. (2018), NPs can disrupt cellular redox homeostasis, but their impact is context-dependent: they can either ameliorate oxidative stress by acting as antioxidants or exacerbate it by promoting the generation of reactive oxygen species (ROS). Also, reactive oxygen species (ROS) are released when a virus infects a plant, rapidly harming the host cells. NPs activate the antioxidant system to combat this. For instance, CeO_2 , CuO , ZnO , TiO_2 , Fe_3O_4 , Al_2O_3 , $\gamma\text{-Fe}_2\text{O}_3$ NPs, CoFe_2O_4 , Ag, and NiO can all decrease oxidative burst in numerous crops and induce an antioxidant system (Soares et al., 2018). Extensive research has demonstrated that metal and metalloid nanoparticles, such as those made from zinc oxide (ZnO), iron oxide (Fe_3O_4), and silicon dioxide (SiO_2), significantly enhance the activity of crucial antioxidant enzymes like peroxidase (POD) and catalase (CAT). By upregulating these key components of the ascorbate-glutathione cycle, the nanoparticles fortify the plant's enzymatic antioxidant defense system. This enhanced activity is a fundamental mechanism for effectively scavenging excess reactive oxygen species (ROS), thereby mitigating oxidative damage to lipids, proteins, and nucleic acids, and ultimately preserving cellular homeostasis and health under stress conditions.

5.6.2 Plant Hormones and Proteins Associated with Pathogenesis

Plant resistance is orchestrated through an intricate network of defense mechanisms, initiated by signaling molecules such as salicylic acid (SA), ethylene (ET), and jasmonic acid (JA). The crosstalk among these and other phytohormones—including cytokinin (CK), gibberellin (GA), strigolactone (SL), auxin (IAA), brassinosteroids (BRs), and abscisic acid (ABA)—fine-tunes the balance between growth and defense. Nanoparticles (NPs) have been shown to significantly influence this hormonal equilibrium, though the outcome depends on the NP type, concentration, and exposure duration (Rastogi et al., 2017). For example: Copper oxide nanoparticles (CuONPs) elevated SA and JA levels in *Arabidopsis thaliana* and upregulated defense-related genes (Landa et al., 2017). In tomato under salt stress, copper nanoparticles combined with hydrogels (Cs-PVA) induced overexpression of JA pathway genes (Hernández-Hernández et al., 2018). Conversely, in *N. benthamiana*, NP application increased SA and ABA but did not alter JA levels (Cai et al., 2020). Silver nanoparticles (AgNPs) enhanced cytokinin (CK) expression in *Capsicum annuum* L. (Vinković et al., 2017) and increased proline content in tomato. Zinc oxide nanoparticles (ZnONPs) exerted dose-dependent effects: low to moderate concentrations promoted CK biosynthesis, while higher levels triggered stress

responses, elevating SA and ABA (Landa et al., 2017). A critical downstream effect of NP-induced hormonal changes is the activation of Pathogenesis-Related (PR) proteins, which serve as hallmark indicators of immune activation. The upregulation of PR1, PR2, and PR5 genes, in particular, signifies activation of the SA-mediated defense pathway (Ali et al., 2018), demonstrating the role of NPs in potentiating systemic acquired resistance (SAR). This body of evidence underscores the potential of nanotechnology to precisely manipulate plant immune responses through hormonal reprogramming, offering novel strategies for enhancing crop resilience.

5.6.3 Secondary Metabolite Production

The mechanism by which nanoparticles (NPs) influence the synthesis of plant secondary metabolites remains unclear, despite numerous studies on the phenomenon. One proposed explanation is that the reactive oxygen species (ROS) generated as a plant's response to NP exposure may interfere with the production of these metabolites (Marslin et al., 2017).

Phenylalanine ammonia-lyase (PAL) acts as a critical regulatory enzyme, connecting primary metabolic processes with the synthesis of secondary metabolites. It catalyzes the initial step in the phenylpropanoid pathway, leading to the production of defense-related compounds such as lignin, salicylic acid, and various phenolic compounds. Its activity is frequently induced under stress conditions and by nanoparticle exposure, reinforcing plant cell walls and activating immune responses. Induced by both biotic and abiotic stress, PAL catalyzes the conversion of phenylalanine to trans-cinnamate, a foundational step for producing compounds like salicylic acid (SA) and jasmonic acid (JA). Empirical evidence demonstrates this NP-mediated activation: treatment with silicon dioxide nanoparticles (SiO₂NPs) was shown to boost JA-induced PAL activity in plants infected with Papaya ringspot virus (PRSV) (Derbalah & Elsharkawy, 2019), while nickel oxide nanoparticles (NiONPs) increased PAL levels in plants infected with Cucumber mosaic virus (CMV) (Elsharkawy & Mousa, 2015). It has been demonstrated that CuONPs affect phenolics and glucosinolates, two phytochemicals found in *Brassica rapa*. According to Chung et al., 2019 study, CuONPs caused this plant's PAL gene to become more active. Research on tobacco plants revealed that treatment with zinc oxide nanoparticles (ZnONPs) similarly resulted in the accumulation of flavonoid and phenolic compounds, along with increased phenylalanine ammonia-lyase (PAL) enzyme activity (Mazaheri-Tirani et al., 2019). In a separate study on potato plants, ZnONPs were also found to elevate levels of anthocyanins and total phenolic content (Raigond et al., 2017). These findings collectively demonstrate the role of ZnONPs in upregulating key pathways of secondary metabolism, enhancing the plant's synthesis of defensive and antioxidant compounds.

5.7 “Applications of Silver, Carbon and Silica Nanoparticles in Agriculture: Enhancing Crop Health and Growth”

Nanotechnology is a very new and fast evolving discipline. Nanoparticles are highly desirable in the domains of biology and materials research due to their special qualities. In recent years, silver nanoparticles, or AgNPs, have become the most popular nanoparticles for use in research. The capacity to accurately control AgNPs’ size, content, and form throughout the nanoscale production process has created a multitude of prospects for utilization in various sectors. Furthermore, in-vivo-synthesised silver nanoparticles have shown promising use in agriculture by lowering crop diseases and enhancing crop nutrient absorption. Ag nanoparticles exhibit bactericidal and inhibitory properties in addition to potent antibacterial properties. It has been shown that the powdery mildew-causing *Sphaerotheca pannosa var rosae* is vulnerable to the antifungal effects of colloidal nano-Ag solution (Kim et al., 2018).

The use of silver nanoparticles (AgNPs) for plant disease management is a rapidly evolving area of agricultural innovation, reflected in the growing number of patents for products such as “Nano silver for diseases abatement in modern agriculture systems.” Studies have established effective green synthesis methods for producing AgNPs using plant extracts. For example, Singh et al. (2021) biosynthesized AgNPs from *Dioscorea bulbifera* L. and found that a concentration of 100 mg/L significantly inhibited the growth of the fungal pathogens *Fusarium oxysporum* and *Colletotrichum gloeosporioides*. Furthermore, Dutta et al. (2022) expanded on this research by producing AgNPs from *Glycosmis pentaphylla* fruit extract and testing their antimicrobial activity against a wide range of bacteria and fungi, including *Escherichia coli*, *Streptococcus mutans*, *Bacillus subtilis*, *Salmonella enterica*, *Alternaria alternata*, *Fusarium moniliforme*, *Colletotrichum lindemuthianum*, and *Candida glabrata*. Their results indicated that the AgNPs were most effective against the fungus *Alternaria alternata* and the bacterium *Bacillus subtilis*, demonstrating strong and targeted antimicrobial potential. Furthermore, *Dickeya dadantii* and *Acidovorax oryzae* were suppressed by Ag nanoparticles made from *Pseudomonas* sp. Based on research by Paul and Roychoudhury (2021), bacterial pathogens such as *Pseudomonas syringae* and *Erwinia* sp. are significant agricultural threats, causing diseases including bacterial soft rot, bacterial stripe, cankers, wilt, leaf spots, and tissue discoloration. Silver nanoparticles (AgNPs) have demonstrated effective antibacterial action against these pathogens, as well as *Citrobacter freundii*.

The antifungal properties of AgNPs are well-documented. According to Kaur et al. (2018), AgNPs inhibit fungal growth by damaging hyphal structures, thereby disrupting nutrient absorption and preventing spore germination and development. AgNPs synthesized from yeast have shown efficacy against a range of fungi, including *Penicillium* sp., *Helminthosporium oryzae*, *Rhizopus* sp., and *Botrytis cinerea* (Paul & Roychoudhury, 2021). Furthermore, these nanoparticles are

effective against wood-degrading fungi like *Gloeophyllum* sp. and the notorious plant pathogen *Phytophthora* sp.

The antifungal efficacy of silver nanoparticles (AgNPs) can be significantly improved by optimizing the green synthesis process, specifically through the use of higher concentrations of natural bioactive compounds derived from medicinal plants. These compounds which include proteins, polysaccharides, organic acids, vitamins, and diverse secondary metabolites act as both reducing and stabilizing agents. By enhancing their concentration during synthesis, the resulting AgNPs exhibit improved stability, morphology, and functional activity, leading to stronger inhibition of fungal pathogens.

Additionally, the antiviral efficacy of AgNPs is influenced by several physico-chemical parameters, including their size (configuration), surface charge, and crystalline structure.

Even though the antiviral's exact mode of action is unknown, Ag nanoparticles' antiviral activity may result from their attachment to the virus surface, where they interact with coat proteins and envelope glycoproteins to prevent virus reproduction. Ag nanoparticles have demonstrated their antiviral properties against many viruses, including tomato spotted wilt, potato, bean yellow mosaic, and sun hemp rosette viruses.

Ag nanoparticles made from *Turbinaria turbinata* and *Ulva lactuca* have additionally demonstrated nematicidal efficacy against infestations of *Meloidogyne incognita* and *Meloidogyne javanica* (Hamed et al., 2019). These nanoparticles reduce egg production, boost larvae mortality through the juvenile phase, limit growth, and reduce the effectiveness of egg hatching, claim Paul and Roychoudhury (2021).

Carbon is the preferred building block for the straightforward synthesis of nanomaterials. Cylindrical carbon allotropes are known as carbon nanotubes (CNTs). These have been used in farming as well as other sectors. The addition of carbon nanotubes (CNTs) to tomato seeds enhanced the plants' capacity to grow and absorb water (Henley et al., 2020). It implies that CNTs protect seeds from disease attack and act as delivery channels for desired compounds to reach seeds during germination. CNTs promote plant growth rather than harming them (Duhan et al., 2017).

Crop plants that are exposed to Si are more resilient to stress and disease (Ma & Yamaji, 2006). Powdery mildew and downy mildew have been treated with aqueous silicate solution. In addition, a number of additional positive outcomes were seen, such as enhanced growth, physiological activity, and agricultural plant tolerance to stress and disease (Kanto et al., 2006). Because silver is a strong disinfectant, it can kill off microbial populations, oligodynamically react to inactivate the enzymes that bacteria use for their metabolic processes, and inhibit the growth of algae (Kim et al., 2017). Due to its strong reactivity, silver's ionic state is unstable; as a result, depending on the physiological environment, silver can be reduced or oxidised. As a result, Ag's antibacterial activity varies. Silver's ionic states are stable in the environment yet have weak antibacterial properties. As a result, Park et al. (2006) created a hybrid of nanosized Si-Ag to guard against a number of plant diseases.

Silica molecules were coupled with this nanoscale hybrid. At 0.3 parts per million, the silica-silver combination has demonstrated remarkable antifungal activity and effectively managed pumpkin powdery mildews. Research into the application of nano-sized silica-silver for fungal control has identified a highly effective concentration for complete growth inhibition. Studies have demonstrated that a concentration of 10 mg/L achieves 100% inhibition against several economically significant fungal pathogens, including *Pythium ultimum*, *Colletotrichum gloeosporioides*, *Magnaporthe grisea*, *Botrytis cinerea*, and *Rhizoctonia solani*. Furthermore, as reported by Prasad et al. (2017), this material also exhibits potent antibacterial properties. At a higher concentration of 100 mg/L, nanosized silica-silver achieved 100% antibacterial activity against a range of bacterial species, such as *Bacillus subtilis*, *Azotobacter chroococcum*, *Pseudomonas syringae*, *Rhizobium tropici*, and *Xanthomonas campestris* pv. *vesicatoria*. This highlights its broad-spectrum potential as a powerful antimicrobial agent in agriculture. However, plants such as pansy and cucumbers have suffered chemical damage due to larger concentrations of this nanosized silica silver (3200 mg/L) (Park et al., 2006). Drug research and treatment can benefit from the usage of silica-based nanomaterials that have been synthesised using silica. As nanocarriers, mesoporous silica nanoparticles improve the effectiveness of traditional pesticides.

5.8 Potential Applications of Nanotechnology in the Agri-food Industries for Disease Control, Detection, and Prevention

Recent advancements in nanotechnology hold transformative potential for revolutionizing disease control, prevention, and protection within the agri-food sector. Although many of these innovations are still in experimental stages, they are poised to bring groundbreaking changes to the industry.

Indeed, nanotechnology offers innovative tools for real-time agricultural diagnostics and precise interventions. Nanomaterials can be engineered to monitor soil conditions—including quality, nutrient levels, and microbial activity—with high sensitivity and responsiveness. Additionally, nanotechnology enhances the delivery of agrochemicals: nanoemulsions, polymer-based nanopesticides, and metal/metal oxide nanoparticle-integrated pesticides enable controlled release and targeted application. This improves efficacy while minimizing the volume of chemicals needed, supporting more sustainable and efficient pest control strategies (Zhang et al., 2023).

Drones equipped with nanosensors can yield insightful information about pest infestations and crop health (Vaseashta, 2020). Nanoparticles, as metal oxide, carbon metal, and other nanocomposites, can be used to remediate soil and water. In addition to the previously mentioned advancements, applying nanocoatings to seeds prior to sowing helps shield crops from pest damage and harmful microbes. Additionally, microorganisms covered with the metal-phenolic network (MPN)

enhance seed germination, increase resistance to environmental stresses, and support the growth of beneficial soil microflora in sensitive environments (Burke et al., 2023). Food packaging is another area where nanotechnology may advance, as nanocomposites may improve food packaging's barrier potential and lengthen its shelf life.

Agriculture's ability to monitor animal health is being revolutionized by research on nanoscale technologies. Similarly, regulated, targeted release of medications and plant nutrition delivery using nanoparticle-based drug delivery technologies are growing quickly. In order to improve nutrient uptake efficiency, lessen the environmental impact of conventional fertilizers, and enable direct nutrient delivery to plant cells, the introduction of nanofertilizer is crucial (Singh et al., 2024). Comparably, another area of nanotechnology with an enormous range of applications is nanoencapsulation. By using nanoparticles to release nutrients gradually, plants can profit from nanoencapsulation and receive an abundant supply of nutrients for long-term use.

5.9 Conclusion

Nanotechnology offers transformative potential in agriculture by boosting plant growth, nutrient uptake, resistance to disease, and precision pesticide application. Eco-friendly nanocapsules enable targeted delivery of agrochemicals, reducing reliance on harmful solvents and improving crop protection. Post-harvest nanotech innovations also help preserve freshness and prevent spoilage. While the environmental effects of nanomaterials require further study, their unique properties suggest promising applications in crop management and plant disease diagnostics. Nanoparticles can facilitate gene delivery, aid in developing disease-resistant crops, and serve as an alternative to viral-based gene silencing methods. Future advancements may include siRNA-loaded nanoparticles for engineering plant immunity. Indeed, although still an emerging field, nanotechnology is opening new pathways to more sustainable, efficient, and innovative agricultural methods. These advancements are critical for tackling pressing worldwide food security issues in an environmentally responsible way.

References

- Abdelkhalek, A., & Al-Askar, A. A. (2020). Green synthesized ZnO nanoparticles mediated by *Mentha spicata* extract induce plant systemic resistance against tobacco mosaic virus. *Applied Sciences*, 10(15), 5054.
- Acharya, A., & Pal, P. K. (2020). Agriculture nanotechnology: Translating research outcome to field applications by influencing environmental sustainability. *NanoImpact*, 19, 100232.

- Adetunji, C. O., & Ugbenyen, M. A. (2019). Mechanism of action of nanopesticide derived from microorganism for the alleviation of abiotic and biotic stress affecting crop productivity. In *Nanotechnology for agriculture: Crop production & protection* (pp. 119–142). Springer.
- Akhtar, M. J., Ahamed, M., Kumar, S., Siddiqui, H., Patil, G., Ashquin, M., & Ahmad, I. (2010). Nanotoxicity of pure silica mediated through oxidant generation rather than glutathione depletion in human lung epithelial cells. *Toxicology*, 276(2), 95–102.
- Ali, S., Ganai, B. A., Kamili, A. N., Bhat, A. A., Mir, Z. A., Bhat, J. A., et al. (2018). Pathogenesis-related proteins and peptides as promising tools for engineering plants with multiple stress tolerance. *Microbiological Research*, 212, 29–37.
- Ali, H. S., Fakhri, M. A., & Khalifa, Z. (2021). Optical and structural properties of the gold nanoparticles ablated by laser ablation in ethanol for biosensors. *Journal of Physics: Conference Series*, 1795(1), 012065. IOP Publishing.
- Alkubaisi, N. A. O., Aref, N. M. M. A., & Hendi, A. A. (2015). *Method of inhibiting plant virus using gold nanoparticles* (US Patents US9198434B1), 1.
- Ardakani, A. S. (2013). Toxicity of silver, titanium and silicon nanoparticles on the root-knot nematode, *Meloidogyne incognita*, and growth parameters of tomato. *Nematology*, 15(6), 671–677.
- Azam, A., Ahmed, A. S., Oves, M., Khan, M. S., & Memic, A. (2012). Size-dependent antimicrobial properties of CuO nanoparticles against Gram-positive and negative bacterial strains. *International Journal of Nanomedicine*, 7, 3527–3535.
- Bautista-Baños, S., Hernandez-Lauzardo, A. N., Velazquez-Del Valle, M. G., Hernández-López, M., Barka, E. A., Bosquez-Molina, E., & Wilson, C. L. (2006). Chitosan as a potential natural compound to control pre and postharvest diseases of horticultural commodities. *Crop Protection*, 25(2), 108–118.
- Bouwmeester, H., Dekkers, S., Noordam, M. Y., Hagens, W. I., Bulder, A. S., De Heer, C., et al. (2009). Review of health safety aspects of nanotechnologies in food production. *Regulatory Toxicology and Pharmacology*, 53(1), 52–62.
- Bryaskova, R., Pencheva, D., Nikolov, S., & Kantardjiev, T. (2011). Synthesis and comparative study on the antimicrobial activity of hybrid materials based on silver nanoparticles (AgNPs) stabilized by polyvinylpyrrolidone (PVP). *Journal of Chemical Biology*, 4, 185–191.
- Burke, B., Fan, G., Wasuwanich, P., Moore, E. B., & Furst, A. L. (2023). Self-assembled nano-coatings protect microbial fertilizers for climate-resilient agriculture. *JACS Au*, 3(11), 2973–2980.
- Cai, L., Cai, L., Jia, H., Liu, C., Wang, D., & Sun, X. (2020). Foliar exposure of Fe₃O₄ nanoparticles on *Nicotiana benthamiana*: Evidence for nanoparticles uptake, plant growth promoter and defense response elicitor against plant virus. *Journal of Hazardous Materials*, 393, 122415.
- Carlson, C., Hussain, S. M., Schrand, A. M., Braydich-Stolle, K., Hess, K. L., Jones, R. L., & Schlager, J. J. (2008). Unique cellular interaction of silver nanoparticles: Size-dependent generation of reactive oxygen species. *The Journal of Physical Chemistry B*, 112(43), 13608–13619.
- Chen, H., & Yada, R. (2011). Nanotechnologies in agriculture: New tools for sustainable development. *Trends in Food Science & Technology*, 22(11), 585–594.
- Chen, M., Hou, C., Huo, D., Bao, J., Fa, H., & Shen, C. (2016). An electrochemical DNA biosensor based on nitrogen-doped graphene/Au nanoparticles for human multidrug resistance gene detection. *Biosensors and Bioelectronics*, 85, 684–691.
- Chirkov, S. N. (2002). The antiviral activity of chitosan. *Applied Biochemistry and Microbiology*, 38, 1–8.
- Choi, S., Han, S. I., Jung, D., Hwang, H. J., Lim, C., Bae, S., et al. (2018). Highly conductive, stretchable and biocompatible Ag–Au core–sheath nanowire composite for wearable and implantable bioelectronics. *Nature Nanotechnology*, 13(11), 1048–1056.

- Chung, I. M., Rekha, K., Venkidasamy, B., & Thiruvengadam, M. (2019). Effect of copper oxide nanoparticles on the physiology, bioactive molecules, and transcriptional changes in *Brassica rapa* ssp. *rapa* seedlings. *Water, Air, & Soil Pollution*, 230, 1–14.
- Cota-Arriola, O., Cortez-Rocha, M. O., Rosas-Burgos, E. C., Burgos-Hernández, A., López-Franco, Y. L., & Plascencia-Jatomea, M. (2011). Antifungal effect of chitosan on the growth of *Aspergillus parasiticus* and production of aflatoxin B1. *Polymer International*, 60(6), 937–944.
- Cromwell, W. A., Yang, J., Starr, J. L., & Jo, Y. K. (2014). Nematicidal effects of silver nanoparticles on root-knot nematode in bermudagrass. *Journal of Nematology*, 46(3), 261.
- Dar, F. A., Qazi, G., & Pirzadah, T. B. (2020). Nano-biosensors: NextGen diagnostic tools in agriculture. In *Nanobiotechnology in agriculture: an approach towards sustainability* (pp. 129–144). Springer.
- Das, K., Jhan, P. K., Das, S. C., Aminuzzaman, F. M., & Ayim, B. Y. (2021). Nanotechnology: Past, present and future prospects in crop protection. In *Technology in agriculture* (pp. 1–22). IntechOpen.
- De, A., Bose, R., Kumar, A., & Mozumdar, S. (2014). *Targeted delivery of pesticides using biodegradable polymeric nanoparticles* (Vol. 10, pp. 978–981). Springer India.
- Derbalah, A. S. H., & Elsharkawy, M. M. (2019). A new strategy to control cucumber mosaic virus using fabricated NiO-nanostructures. *Journal of Biotechnology*, 306, 134–141.
- Deshpande, P., Dapkekar, A., Oak, M. D., Paknikar, K. M., & Rajwade, J. M. (2017). Zinc complexed chitosan/TPP nanoparticles: A promising micronutrient nanocarrier suited for foliar application. *Carbohydrate Polymers*, 165, 394–401.
- Dimri, A., Pathak, N., & Sharma, S. (2020). Nanosensors for root zone parameters influencing plant growth. In *Nanomaterials for agriculture and forestry applications* (pp. 387–406). Elsevier.
- Dizaj, S. M., Lotfipour, F., Barzegar-Jalali, M., Zarrintan, M. H., & Adibkia, K. (2014). Antimicrobial activity of the metals and metal oxide nanoparticles. *Materials Science and Engineering: C*, 44, 278–284.
- Duhan, J. S., Kumar, R., Kumar, N., Kaur, P., Nehra, K., & Duhan, S. (2017). Nanotechnology: The new perspective in precision agriculture. *Biotechnology Reports*, 15, 11–23.
- Dutta, T., Chowdhury, S. K., Ghosh, N. N., Chattopadhyay, A. P., Das, M., & Mandal, V. (2022). Green synthesis of antimicrobial silver nanoparticles using fruit extract of *Glycosmis pentaphylla* and its theoretical explanations. *Journal of Molecular Structure*, 1247, 131361.
- Elmer, W., De La Torre-Roche, R., Pagano, L., Majumdar, S., Zuverza-Mena, N., Dimkpa, C., et al. (2018). Effect of metalloid and metal oxide nanoparticles on fusarium wilt of watermelon. *Plant Disease*, 102(7), 1394–1401.
- Elsharkawy, M. M., & Derbalah, A. (2019). Antiviral activity of titanium dioxide nanostructures as a control strategy for broad bean strain virus in faba bean. *Pest Management Science*, 75(3), 828–834.
- Elsharkawy, M. M., & Mousa, K. M. (2015). Induction of systemic resistance against papaya ring spot virus (PRSV) and its vector *Myzus persicae* by penicillium simplicissimum GP17-2 and silica (SiO₂) nanopowder. *International Journal of Pest Management*, 61(4), 353–358.
- Firrao, G., Moretti, M., Rosquete, M. R., Gobbi, E., & Locci, R. (2005). Nanobiotransducer for detecting flavescence dorée phytoplasma. *Journal of Plant Pathology*, 87, 101–107.
- Flood, J. (2010). The importance of plant health to food security. *Food Security*, 2(3), 215–231.
- Fu, P. P., Xia, Q., Hwang, H. M., Ray, P. C., & Yu, H. (2014). Mechanisms of nanotoxicity: Generation of reactive oxygen species. *Journal of Food and Drug Analysis*, 22(1), 64–75.
- Gan, N., Yang, X., Xie, D., Wu, Y., & Wen, W. (2010). A disposable organophosphorus pesticides enzyme biosensor based on magnetic composite nano-particles modified screen printed carbon electrode. *Sensors*, 10(1), 625–638.
- Gao, C. (2021). Genome engineering for crop improvement and future agriculture. *Cell*, 184(6), 1621–1635.
- Gleiter, H. (2000). Nanostructured materials: Basic concepts and microstructure. *Acta Materialia*, 48(1), 1–29.

- Gonzalez Guzman, M., Cellini, F., Fotopoulos, V., Balestrini, R., & Arbona, V. (2022). New approaches to improve crop tolerance to biotic and abiotic stresses. *Physiologia Plantarum*, 174(1), e13547.
- Ha, N. T., Minh, T. Q., Hoi, P. X., Thuy, N. T. T., Furuya, N., & Long, H. H. (2018). Biological control of potato tuber soft rot using N-acyl-L-homoserine lactone-degrading endophytic bacteria. *Current Science*, 115(10), 1921–1927.
- Hamed, S. M., Hagag, E. S., & El-Raouf, N. A. (2019). Green production of silver nanoparticles, evaluation of their nematocidal activity against *Meloidogyne javanica* and their impact on growth of faba bean. *Beni-Suef University Journal of Basic and Applied Sciences*, 8, 1–12.
- Hamid, A., & Saleem, S. (2022). Role of nanoparticles in management of plant pathogens and scope in plant transgenics for imparting disease resistance. *Plant Protection Science*, 58(3), 173–184.
- Hayles, J., Johnson, L., Worthley, C., & Losic, D. (2017). Nanopesticides: A review of current research and perspectives. In *New pesticides and soil sensors* (pp. 193–225). Academic Press.
- Hermida-Montero, L. A., Pariona, N., Mtz-Enriquez, A. I., Carrión, G., Paraguay-Delgado, F., & Rosas-Saito, G. (2019). Aqueous-phase synthesis of nanoparticles of copper/copper oxides and their antifungal effect against *Fusarium oxysporum*. *Journal of Hazardous Materials*, 380, 120850.
- Hernández-Hernández, H., Juárez-Maldonado, A., Benavides-Mendoza, A., Ortega-Ortiz, H., Cadenas-Pilego, G., Sánchez-Aspeytia, D., & González-Morales, S. (2018). Chitosan-PVA and copper nanoparticles improve growth and overexpress the SOD and JA genes in tomato plants under salt stress. *Agronomy*, 8(9), 175.
- Hoseinnejad, M., Jafari, S. M., & Katouzian, I. (2018). Inorganic and metal nanoparticles and their antimicrobial activity in food packaging applications. *Critical Reviews in Microbiology*, 44(2), 161–181.
- Huang, L., Cheng, X., Liu, C., Xing, K., Zhang, J., Sun, G., et al. (2009). Preparation, characterization, and antibacterial activity of oleic acid-grafted chitosan oligosaccharide nanoparticles. *Frontiers of Biology in China*, 4, 321–327.
- Ijaz, U., Ahmed, T., Rizwan, M., Noman, M., Shah, A. A., Azeem, F., et al. (2023). Rice straw based silicon nanoparticles improve morphological and nutrient profile of rice plants under salinity stress by triggering physiological and genetic repair mechanisms. *Plant Physiology and Biochemistry*, 201, 107788.
- Jayaseelan, C., Rahuman, A. A., Kirthi, A. V., Marimuthu, S., Santhoshkumar, T., Bagavan, A., et al. (2012). Novel microbial route to synthesize ZnO nanoparticles using *Aeromonas hydrophila* and their activity against pathogenic bacteria and fungi. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 90, 78–84.
- Jeeran, I., Sonsa-Ard, T., & Nacapricha, D. (2020). Applying nanomaterials to modern biomedical electrochemical detection of metabolites, electrolytes, and pathogens. *Chem*, 8(3), 71.
- Joshi, S. M., De Britto, S., & Jogaiah, S. (2021). Myco-engineered selenium nanoparticles elicit resistance against tomato late blight disease by regulating differential expression of cellular, biochemical and defense responsive genes. *Journal of Biotechnology*, 325, 196–206.
- Jung, K. W., Cheong, K. H., Woo, K. K., Sook, S., Hyun, K. S., & Ho, P. Y. (2008). Antibacterial activity and mechanism of action of the silver ion in *Staphylococcus aureus* and *Escherichia coli*. *Applied and Environmental Microbiology*, 74, 2171–2178.
- Kah, M., & Hofmann, T. (2014). Nanopesticide research: Current trends and future priorities. *Environment International*, 63, 224–235.
- Kanto, T., Miyoshi, A., Ogawa, T., Maekawa, K., & Aino, M. (2006). Suppressive effect of liquid potassium silicate on powdery mildew of strawberry in soil. *Journal of General Plant Pathology*, 72, 137–142.
- Kaur, P., Thakur, R., Duhan, J. S., & Chaudhury, A. (2018). Management of wilt disease of chickpea in vivo by silver nanoparticles biosynthesized by rhizospheric microflora of chickpea (*Cicer arietinum*). *Journal of Chemical Technology & Biotechnology*, 93(11), 3233–3243.
- Khan, M. R., & Rizvi, T. F. (2014). Nanotechnology: Scope and application in plant disease management. *Plant Pathology Journal*, 13(3), 214–231.

- Khandelwal, N., Barbole, R. S., Banerjee, S. S., Chate, G. P., Biradar, A. V., Khandare, J. J., & Giri, A. P. (2016). Budding trends in integrated pest management using advanced micro-and nano-materials: Challenges and perspectives. *Journal of Environmental Management*, 184, 157–169.
- Khezerlou, A., Alizadeh-Sani, M., Azizi-Lalabadi, M., & Ehsani, A. (2018). Nanoparticles and their antimicrobial properties against pathogens including bacteria, fungi, parasites and viruses. *Microbial Pathogenesis*, 123, 505–526.
- Kim, D. H., Gopal, J., & Sivanesan, I. (2017). Nanomaterials in plant tissue culture: The disclosed and undisclosed. *RSC Advances*, 7(58), 36492–36505.
- Kim, D. Y., Kadam, A., Shinde, S., Saratale, R. G., Patra, J., & Ghodake, G. (2018). Recent developments in nanotechnology transforming the agricultural sector: A transition replete with opportunities. *Journal of the Science of Food and Agriculture*, 98(3), 849–864.
- Koseoglou, E., van der Wolf, J. M., Visser, R. G., & Bai, Y. (2022). Susceptibility reversed: Modified plant susceptibility genes for resistance to bacteria. *Trends in Plant Science*, 27(1), 69–79.
- Krishnaraj, C., Ramachandran, R., Mohan, K., & Kalaichelvan, P. T. (2012). Optimization for rapid synthesis of silver nanoparticles and its effect on phytopathogenic fungi. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 93, 95–99.
- Kumar, S., Nehra, M., Dilbaghi, N., Marrazza, G., Hassan, A. A., & Kim, K. H. (2019). Nano-based smart pesticide formulations: Emerging opportunities for agriculture. *Journal of Controlled Release*, 294, 131–153.
- Kurtjak, M., Anicic, N., & Vukomanovic, M. (2017). Inorganic nanoparticles: Innovative tools for antimicrobial agents. In *Antibacterial agents*. IntechOpen.
- Kutawa, A. B., Ahmad, K., Ali, A., Hussein, M. Z., Abdul Wahab, M. A., Adamu, A., et al. (2021). Trends in nanotechnology and its potentialities to control plant pathogenic fungi: A review. *Biology*, 10(9), 881.
- Landa, P., Dytrych, P., Prerostova, S., Petrova, S., Vankova, R., & Vanek, T. (2017). Transcriptomic response of *Arabidopsis thaliana* exposed to CuO nanoparticles, bulk material, and ionic copper. *Environmental Science & Technology*, 51(18), 10814–10824.
- Lattanzio, V. M., & Nivarlet, N. (2017). Multiplex dipstick immunoassay for semiquantitative determination of fusarium mycotoxins in oat. *Methods in Molecular Biology*, 1536, 137–142.
- Lau, H. Y., Wu, H., Wee, E. J., Trau, M., Wang, Y., & Botella, J. R. (2017). Specific and sensitive isothermal electrochemical biosensor for plant pathogen DNA detection with colloidal gold nanoparticles as probes. *Scientific Reports*, 7(1), 38896.
- Lisa, M., Chouhan, R. S., Vinayaka, A. C., Manonmani, H. K., & Thakur, M. S. (2009). Gold nanoparticles based dipstick immunoassay for the rapid detection of dichlorodiphenyltrichloroethane: An organochlorine pesticide. *Biosensors and Bioelectronics*, 25(1), 224–227.
- Liu, Q., Li, Y., Xu, K., Li, D., Hu, H., Zhou, F., et al. (2020). Clay nanosheet-mediated delivery of recombinant plasmids expressing artificial miRNAs via leaf spray to prevent infection by plant DNA viruses. *Horticulture Research*, 7, 179.
- Ma, J. F., & Yamaji, N. (2006). Silicon uptake and accumulation in higher plants. *Trends in Plant Science*, 11(8), 392–397.
- Majeed, Z. H., & Taha, M. R. (2013). A review of stabilization of soils by using nanomaterials. *Australian Journal of Basic and Applied Sciences*, 7(2), 576–581.
- Marslin, G., Sheeba, C. J., & Franklin, G. (2017). Nanoparticles alter secondary metabolism in plants via ROS burst. *Frontiers in Plant Science*, 8, 832.
- Martínez-Camacho, A. P., Cortez-Rocha, M. O., Ezquerro-Brauer, J. M., Graciano-Verdugo, A. Z., Rodríguez-Félix, F., Castillo-Ortega, M. M., et al. (2010). Chitosan composite films: Thermal, structural, mechanical and antifungal properties. *Carbohydrate Polymers*, 82(2), 305–315.
- Medintz, I. L., Sapsford, K. E., Konner, J. H., Chatterji, A., Lin, T., Johnson, J. E., & Mattoussi, H. (2005). Decoration of discretely immobilized cowpea mosaic virus with luminescent quantum dots. *Langmuir*, 21(12), 5501–5510.

- Miao, Y., Zhao, S., Gao, Y., Wang, R., Wu, Q., Wu, H., & Luo, T. (2016). Curcumin pretreatment attenuates inflammation and mitochondrial dysfunction in experimental stroke: The possible role of Sirt1 signaling. *Brain Research Bulletin*, 121, 9–15.
- Mittapally, S., Taranum, R., & Parveen, S. (2018). Metal ions as antibacterial agents. *Journal of Drug Delivery and Therapeutics*, 8(6-s), 411–419.
- Mitter, N., Worrall, E. A., Robinson, K. E., Li, P., Jain, R. G., Taochy, C., et al. (2017). Clay nanosheets for topical delivery of RNAi for sustained protection against plant viruses. *Nature Plants*, 3(2), 1–10.
- Mukhopadhyay, S. S. (2014). Nanotechnology in agriculture: Prospects and constraints. *Nanotechnology, Science and Applications*, 7, 63–71.
- Nair, R., Varghese, S. H., Nair, B. G., Maekawa, T., Yoshida, Y., & Kumar, D. S. (2010). Nanoparticulate material delivery to plants. *Plant Science*, 179(3), 154–163.
- Nandini, B., Hariprasad, P., Prakash, H. S., Shetty, H. S., & Geetha, N. (2017). Trichogenic-selenium nanoparticles enhance disease suppressive ability of Trichoderma against downy mildew disease caused by *Sclerospora graminicola* in pearl millet. *Scientific Reports*, 7(1), 2612.
- Narasimhamurthy, K., Udayashankar, A. C., De Britto, S., Lavanya, S. N., Abdelrahman, M., Soumya, K., et al. (2022). Chitosan and chitosan-derived nanoparticles modulate enhanced immune response in tomato against bacterial wilt disease. *International Journal of Biological Macromolecules*, 220, 223–237.
- Nassar, A. M. (2016). Research article effectiveness of silver nano-particles of extracts of *Urtica urens* (Urticaceae) against root-knot nematode *meloidogyne incognita*. *Asian Journal of Nematology*, 5, 14–19.
- Nile, S. H., Thiruvengadam, M., Wang, Y., Samynathan, R., Shariati, M. A., Rebezov, M., et al. (2022). Nano-priming as emerging seed priming technology for sustainable agriculture—Recent developments and future perspectives. *Journal of Nanobiotechnology*, 20(1), 254.
- Özel, R. E., Alkasir, R. S., Ray, K., Wallace, K. N., & Andreescu, S. (2013). Comparative evaluation of intestinal nitric oxide in embryonic zebrafish exposed to metal oxide nanoparticles. *Small*, 9(24), 4250–4261.
- Palma-Guerrero, J., Lopez-Jimenez, J. A., Pérez-Berná, A. J., Huang, I. C., Jansson, H. B., Salinas, J., et al. (2010). Membrane fluidity determines sensitivity of filamentous fungi to chitosan. *Molecular Microbiology*, 75(4), 1021–1032.
- Panpatte, D. G., & Jhala, Y. K. (Eds.). (2019). *Nanotechnology for agriculture: Crop production & protection*. Springer Nature.
- Pariona, N., Paraguay-Delgado, F., Basurto-Cereceda, S., Morales-Mendoza, J. E., Hermida-Montero, L. A., & Mtz-Enriquez, A. I. (2020). Shape-dependent antifungal activity of ZnO particles against phytopathogenic fungi. *Applied Nanoscience*, 10, 435–443.
- Park, H. J., Kim, S. H., Kim, H. J., & Choi, S. H. (2006). A new composition of nanosized silica-silver for control of various plant diseases. *Plant Pathology Journal*, 22(3), 295–302.
- Paul, A., & Roychoudhury, A. (2021). Go green to protect plants: Repurposing the antimicrobial activity of biosynthesized silver nanoparticles to combat phytopathogens. *Nanotechnology For Environmental Engineering*, 6(1), 10.
- Prasad, R., Bhattacharyya, A., & Nguyen, Q. D. (2017). Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. *Frontiers in Microbiology*, 8, 1014.
- Raffi, M., Hussain, F., Bhatti, T. M., Akhter, J. I., Hameed, A., & Hasan, M. M. (2008). Antibacterial characterization of silver nanoparticles against *E. coli* ATCC-15224. *Journal of Materials Science and Technology*, 24(2), 192–196.
- Ragaei, M., & Sabry, A. K. H. (2014). Nanotechnology for insect pest control. *International Journal of Science, Environment and Technology*, 3(2), 528–545.
- Raigond, P., Raigond, B., Kaundal, B., Singh, B., Joshi, A., & Dutt, S. (2017). Effect of zinc nanoparticles on antioxidative system of potato plants. *Journal of Environmental Biology*, 38(3), 435.
- Rastogi, A., Zivcak, M., Sytar, O., Kalaji, H. M., He, X., Mbarki, S., & Brestic, M. (2017). Impact of metal and metal oxide nanoparticles on plant: A critical review. *Frontiers in Chemistry*, 5, 78.

- Ray, M. K., Mishra, A. K., Mohanta, Y. K., Mahanta, S., Chakrabartty, I., Kungwani, N. A., et al. (2023). Nanotechnology as a promising tool against phytopathogens: A futuristic approach to agriculture. *Agriculture*, 13(9), 1856.
- Rico, C. M., Peralta-Videa, J. R., & Gardea-Torresdey, J. L. (2015). Chemistry, biochemistry of nanoparticles, and their role in antioxidant defense system in plants. In *Nanotechnology and plant sciences: Nanoparticles and their impact on plants* (pp. 1–17). Springer.
- Rodriguez-Moreno, L., Song, Y., & Thomma, B. P. (2017). Transfer and engineering of immune receptors to improve recognition capacities in crops. *Current Opinion in Plant Biology*, 38, 42–49.
- Romanovski, V., & Periakaruppan, R. (2023). Why metal oxide nanoparticles are superior to other nanomaterials for agricultural application? In *Nanometal oxides in horticulture and agronomy* (pp. 7–18). Academic.
- Sangeetha, J., Mundaragi, A., Thangadurai, D., Maxim, S. S., Pandhari, R. M., & Alabhai, J. M. (2019). Nanobiotechnology for agricultural productivity, food security and environmental sustainability. In *Nanotechnology for Agriculture: Crop Production & Protection* (pp. 1–23). Springer.
- Saxena, K. K., Qian, J., & Reynaerts, D. (2018). A review on process capabilities of electrochemical micromachining and its hybrid variants. *International Journal of Machine Tools and Manufacture*, 127, 28–56.
- Shafiq, F., Iqbal, M., Ali, M., & Ashraf, M. A. (2019). Seed pre-treatment with polyhydroxy fullerene nanoparticles confer salt tolerance in wheat through upregulation of H₂O₂ neutralizing enzymes and phosphorus uptake. *Journal of Soil Science and Plant Nutrition*, 19, 734–742.
- Shoala, T. (2021). Dual role of nanoparticles in plant growth and phytopathogen management. In *Nanotechnology in plant growth promotion and protection: Recent advances and impacts* (pp. 203–219). Wiley.
- Shojaei, T. R., Salleh, M. A. M., Sijam, K., Rahim, R. A., Mohsenifar, A., Safarnejad, R., & Tabatabaei, M. (2016). Detection of citrus tristeza virus by using fluorescence resonance energy transfer-based biosensor. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 169, 216–222.
- Siddiqui, M. H., Al-Whaibi, M. H., Firoz, M., & Al-Khaishany, M. Y. (2015). Role of nanoparticles in plants. In *Nanotechnology and plant sciences: nanoparticles and their impact on plants* (pp. 19–35). Springer.
- Singh, K., Madhusudanan, M., Verma, A. K., Kumar, C., & Ramawat, N. (2021). Engineered zinc oxide nanoparticles: An alternative to conventional zinc sulphate in neutral and alkaline soils for sustainable wheat production. *3 Biotech*, 11(7), 322.
- Singh, P., Khan, D., & Kumar, A. (2024). Introduction to nanopesticides, nanoherbicides, and nanofertilizers. In *Nanopesticides, nanoherbicides, and nanofertilizers* (pp. 1–25). CRC Press.
- Soares, C., Pereira, R., & Fidalgo, F. (2018). Metal-based nanomaterials and oxidative stress in plants: Current aspects and overview. *Phytotoxicity of Nanoparticles*, 11, 197–227.
- Stanisic, D., Costa, A. F., Cruz, G., Durán, N., & Tasic, L. (2018). Applications of flavonoids, with an emphasis on hesperidin, as anticancer prodrugs: Phytotherapy as an alternative to chemotherapy. *Studies in Natural Products Chemistry*, 58, 161–212.
- Sun, W., Zhong, J., Qin, P., & Jiao, K. (2008). Electrochemical biosensor for the detection of cauliflower mosaic virus 35 S gene sequences using lead sulfide nanoparticles as oligonucleotide labels. *Analytical Biochemistry*, 377(2), 115–119.
- Sun, L., Nasrullah, Ke, F., Nie, Z., Wang, P., & Xu, J. (2019). Citrus genetic engineering for disease resistance: Past, present and future. *International Journal of Molecular Sciences*, 20(21), 5256.
- Tan, B. L., Norhaizan, M. E., Liew, W. P. P., & Sulaiman Rahman, H. (2018). Antioxidant and oxidative stress: A mutual interplay in age-related diseases. *Frontiers in Pharmacology*, 9, 1162.
- Tirani, M. M., Haghjou, M. M., & Ismaili, A. (2019). Hydroponic grown tobacco plants respond to zinc oxide nanoparticles and bulk exposures by morphological, physiological and anatomical adjustments. *Functional Plant Biology*, 46(4), 360–375.

- Tiwari, M., Pati, D., Mohapatra, R., Sahu, B. B., & Singh, P. (2022). The impact of microbes in plant immunity and priming induced inheritance: A sustainable approach for crop protection. *Plant Stress*, 4, 100072.
- Umapathi, R., Ghoreishian, S. M., Sonwal, S., Rani, G. M., & Huh, Y. S. (2022). Portable electrochemical sensing methodologies for on-site detection of pesticide residues in fruits and vegetables. *Coordination Chemistry Reviews*, 453, 214305.
- US Environmental Protection Agency. (2007). *Nanotechnology white paper; report EPA 100/B-07/001* (Vol. 1). US Environmental Protection Agency.
- Valko, M., Rhodes, C. J. B., Moncol, J., Izakovic, M. M., & Mazur, M. (2006). Free radicals, metals and antioxidants in oxidative stress-induced cancer. *Chemico-Biological Interactions*, 160(1), 1–40.
- Vaseashta, A. (2020). Cyber-physical systems—Nanomaterial sensors based unmanned aerial platforms for real-time monitoring and analysis. In *4th International conference on nanotechnologies and biomedical engineering: Proceedings of ICNBME-2019, September 18–21, 2019, Chisinau, Moldova* (pp. 685–689). Springer.
- Vaseghi, A., Safaie, N., Bakhshinejad, B., Mohsenifar, A., & Sadeghizadeh, M. (2013). Detection of pseudomonas syringae pathovars by thiol-linked DNA–gold nanoparticle probes. *Sensors and Actuators B: Chemical*, 181, 644–651.
- Vinković, T., Novák, O., Strnad, M., Goessler, W., Jurašin, D. D., Paradiković, N., & Vrček, I. V. (2017). Cytokinin response in pepper plants (*Capsicum annuum* L.) exposed to silver nanoparticles. *Environmental Research*, 156, 10–18.
- Wahabzada, M., Mahlein, A. K., Bauckhage, C., Steiner, U., Oerke, E. C., & Kersting, K. (2016). Plant phenotyping using probabilistic topic models: Uncovering the hyperspectral language of plants. *Scientific Reports*, 6(1), 22482.
- Wally, O., & Punja, Z. K. (2010). Genetic engineering for increasing fungal and bacterial disease resistance in crop plants. *GM Crops*, 1(4), 199–206.
- Wang, P. C., Zhao, S., Yang, B. Y., Wang, Q. H., & Kuang, H. X. (2016). Anti-diabetic polysaccharides from natural sources: A review. *Carbohydrate Polymers*, 148, 86–97.
- Wardman, P., & Candeias, L. P. (1996). Fenton chemistry: An introduction. *Radiation Research*, 145(5), 523–531.
- Warghane, A., Saini, R., Shri, M., Andankar, I., Ghosh, D. K., & Chopade, B. A. (2024). Application of nanoparticles for management of plant viral pathogen: Current status and future prospects. *Virology*, 592, 109998.
- Xiao, Z., Fan, N., Zhu, W., Qian, H. L., Yan, X. P., Wang, Z., & Rasmann, S. (2023). Silicon nanodots increase plant resistance against herbivores by simultaneously activating physical and chemical defenses. *ACS Nano*, 17(3), 3107–3118.
- Yan, J., Huang, K., Wang, Y., & Liu, S. (2005). Study on anti-pollution nano-preparation of dimethomorph and its performance. *Chinese Science Bulletin*, 50, 108–112.
- Yan, X., Chen, S., Pan, Z., Zhao, W., Rui, Y., & Zhao, L. (2022). AgNPs-triggered seed metabolic and transcriptional reprogramming enhanced rice salt tolerance and blast resistance. *ACS Nano*, 17(1), 492–504.
- Yang, Z., Zhi, P., & Chang, C. (2022). Priming seeds for the future: Plant immune memory and application in crop protection. *Frontiers in Plant Science*, 13, 961840.
- Yao, K. S., Li, S. J., Tzeng, K. C., Cheng, T. C., Chang, C. Y., Chiu, C. Y., et al. (2009). Fluorescence silica nanoprobe as a biomarker for rapid detection of plant pathogens. *Advanced Materials Research*, 79, 513–516.
- Yazgan, I., Zhang, J., Kariuki, V., Akgul, A., Cronmiller, L. E., Akgul, A., et al. (2018). Selective sensing and imaging of penicillium italicum spores and hyphae using carbohydrate–lectin interactions. *ACS Sensors*, 3(3), 648–654.
- Yazgan, I., Osonga, F. J., Miller, R. M., Kariuki, V. M., Zhang, J., Feng, J., et al. (2021). Greener one-pot synthesis of gold nanoparticle glycoconjugates using functionalized sugars. *ACS Agricultural Science & Technology*, 1(4), 379–389.

- Yearla, S. R., & Padmasree, K. (2016). Exploitation of subabul stem lignin as a matrix in controlled release agrochemical nanoformulations: A case study with herbicide diuron. *Environmental Science and Pollution Research*, 23, 18085–18098.
- Zain, M., Ma, H., Nuruzzaman, M., Chaudhary, S., Nadeem, M., Shakoor, N., et al. (2023). Nanotechnology based precision agriculture for alleviating biotic and abiotic stress in plants. *Plant Stress*, 10, 100239.
- Zhang, M., Chen, W., Chen, X., Zhang, Y., Lin, X., Wu, Z., & Li, M. (2013). Multiplex immunoassays of plant viruses based on functionalized upconversion nanoparticles coupled with immunomagnetic separation. *Journal of Nanomaterials*, 2013(1), 317437.
- Zhang, Z., Zhang, Q., Li, L., Lin, D., & Jiang, C. (2023). Ultrasensitive and on-site detection of carbaryl pesticides via dual-mode nanosensors utilizing portable devices. *ACS Sustainable Chemistry & Engineering*, 11(13), 4998–5006.
- Zhao, L., Lu, L., Wang, A., Zhang, H., Huang, M., Wu, H., et al. (2020). Nano-biotechnology in agriculture: Use of nanomaterials to promote plant growth and stress tolerance. *Journal of Agricultural and Food Chemistry*, 68(7), 1935–1947.
- Zhou, H. Y., Zhou, D. J., Zhang, W. F., Jiang, L. J., Li, J. B., & Chen, X. G. (2011). Biocompatibility and characteristics of chitosan/cellulose acetate microspheres for drug delivery. *Frontiers of Materials Science*, 5, 367–378.

Chapter 6

Future Developments of Nanoparticle's Application for Plant Disease Management and Sustainable Yields



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Abstract Nanotechnology has shown promising potential to promote sustainable agriculture. This article reviews the importance and application of nanoparticles in agriculture as nano fertilizers and nano pesticides, fate of nanoparticles in soil, used for the protection of plant and also act as smart delivery system. Nanoparticles have become a pivotal innovation in agriculture, offering solutions to enhance productivity and sustainability. The emergence of engineered nanomaterials and their actions within the frame of sustainable agriculture have revolutionized world agriculture canvass dramatically by novelty, fast growth and enormity to meet the projection of global food demand. Application of nanotechnology is highly recommended in agricultural production as it increases the quality as well as quantity of yields. Nanotechnology can also be helpful in reducing soil, water and air pollution caused due to excessive use of agrochemicals, thus making agriculture more sustainable. Nanomaterials function as unique carriers of agrochemicals thus facilitate the site-targeted controlled delivery of nutrients with increased crop protection. They offer a wider specific surface area to fertilizers and pesticides. Nanomaterials can enhance nutrient uptake by providing nano-forms of essential nutrients, which are more

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readily absorbed by plant roots. This leads to improved growth and development. Nanomaterials play an important role regarding the fate, mobility and toxicity of soil pollutants and are essential part of different biotic and abiotic remediation strategies. Efficiency and fate of nanomaterials is strongly dictated by their properties and interactions with soil constituents which is also critically discussed in this review. This review also discusses about the recent developments in the use of nanoparticles in plant growth promotion, types of nanoparticles used their mechanism of action, current applications and their future outcomes.

Keywords Nanotechnology · Nanomaterials · Nanoparticles · Nanofertilizers · Nanopesticides

6.1 Introduction

Growing technical expertise has significantly improved scientific communities' ability to reason logically and shape theoretical conceptions into research that is almost exclusively focused on products. "There's plenty of room at the bottom" was one of Feynman's imaginative thoughts that led to the identification and development of nanotechnology to become one of the major emerging technologies of the decade (Toumey, 2008). The advancement of application properties has been greatly aided by the introduction of nanotechnology into various industries. In the current situation, the agricultural sector needs to ensure that the world's population, which is growing at a rapid rate, has access to enough food. Regrettably, during the time from production to consumption, it is estimated that around one-third of the world's crop production is wasted annually. Various technical solutions are emerging to deal with this and improve post-harvest standards in order to avoid loss of agricultural produce. In order to satisfy the future requirements of the growing global population of people, higher agricultural output is dependent on plant mineral content. The goal of nanotechnology is to replace conventional bulk chemical fertilizers with their superior nanoparticulate counterparts, which have better properties and can overcome the current challenges of accessibility and mineral uptake, increase crop yield, decrease fertilizer waste, and protect the environment (Achari & Kowshik, 2018). With the use of these cutting-edge materials, precision agriculture is evolving from modern agriculture to maximize output while utilizing the resources at hand. Other NMs, including nanotubes, nanoclays & nanowires, have different surface chemical, electrical, and optical characteristics that provide them increased sensitivity, greater detection limits, & quicker reaction times. Fertilizers are required to increase crop yields, but they can reduce soil fertility by upsetting the balance of minerals in the soil (Mittal et al., 2020). Nanoagroparticles are particles of nanosized size intended to mitigate issues associated with the agricultural industry. These nanoagroparticles are effective herbicides, insecticides, fungicidal and insecticidal agents, and factors that promote plant growth (Baker et al., 2017b). Because they are biodegradable and potentially non-toxic, lignocellulosic-based nanopesticides present an intriguing platform for the development of safe-by-design nanopesticides (Agathokleous

et al., 2020). Furthermore, it is possible to collect lignocellulosic material from agricultural based streams, which is perfect for cutting costs for producing nanopesticides, which are meant to be used in large-scale agricultural operations. Additionally, this approach shows a plant-to-plant effort, which is perfect for the circular bioeconomy environment (de Lima et al., 2021). In addition to pectin, tannins, acids, and proteins, the three main non-edible lignocellulosic biopolymers that are currently used in the development of products are cellulose, lignin, as well as hemicellulose (Okolie et al., 2021). Although lignocellulosic materials possess low production costs and environmentally friendly qualities, the manipulation of their feedstock presents a challenge to engineers (Li et al., 2021). While there are still various developments to be made in the field of lignocellulosic-based nanocarriers towards the agricultural industry, these advancements make the technology valuable for nano-enabled agriculture.

With an anticipated 9.6 billion people on the planet by 2050, agricultural output will need to rise by 70–100% to keep up with demand for food. However, the effects of climate change, the depletion of arable land, the scarcity of water resources, and the inefficient use of modern agrochemicals exacerbate biotic and abiotic stresses on crops, reducing their yields (Rodrigues et al., 2017). Drought and salinity, for instance, result in annual crop losses of billions of dollars. Therefore, increasing food production is a pressing issue. Strong salt-tolerant wheat cultivars that are commercially available have not yet been created, and efforts to produce crop varieties that can withstand stress have been sluggish. In addition, a lot of people are worried about how safe transgenic crops are (Raliya et al., 2018). Nanotechnology is the study of materials that are smaller than 100 nm in a minimum of one dimension and that are manipulable at the molecular or atomic level. Among its numerous uses, those are being investigated more and more as a potential method to boost crop productivity and encourage plant development. Engineered nanoparticles have demonstrated encouraging benefits in the germination and care of seeds, plant development, and development, hazardous agrochemicals, and pathogen detection (Shabala et al., 2014). Thus, using methods other than chemical and genetic engineering, plant nanobiotechnology may support sustainable agricultural output. Therefore, through mechanisms, plant nanobiotechnology may support sustainable agricultural output different from genetic and chemical engineering. Nanoparticles (NPs) are great nanocarriers for bioactive materials like plasmid DNA and double-stranded RNA because of their minuscule size, massive surface area, and numerous binding sites (Mueller et al., 2012). Figure 6.1 is an illustration of the mechanism by which nanoparticles interact with plants.

Avellan et al.'s investigation shown that surface-modified AuNPs applied topically can penetrate mesophyll, roots, as well as the rhizosphere soil through root exudates. These findings illustrated NPs' potential in the precise distribution of nutrients to particular plant organelles or tissues, lowering the quantity of agrochemicals used required or boosting the bioavailability of inadequately available soil nutrients (Giraldo et al., 2019). Internalization process of nanoparticles in different plant sections shown in Fig. 6.2.

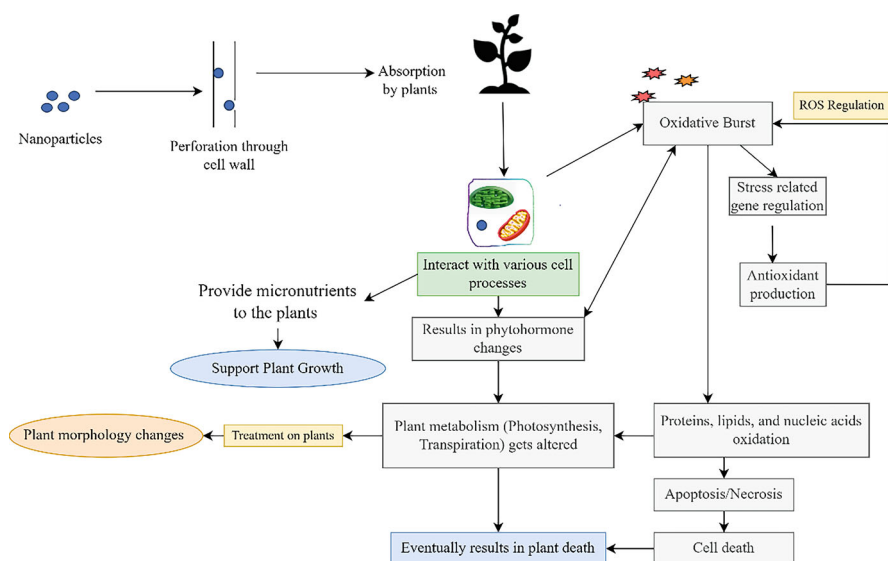


Fig. 6.1 An illustration of the mechanism by which nanoparticles interact with plants

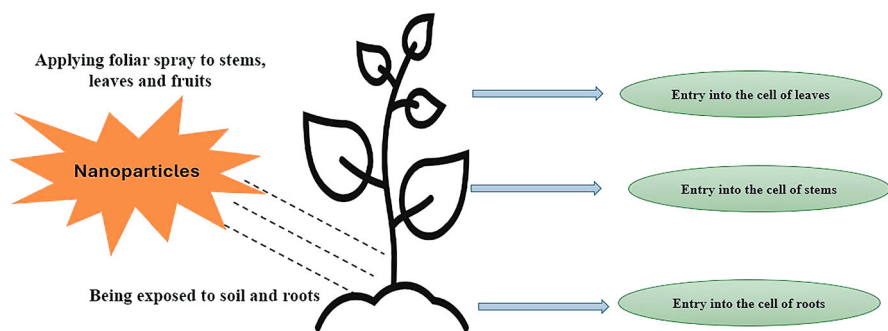


Fig. 6.2 Nanoparticles' internalisation process in different plant sections

Additionally, NPs have special optoelectronic, physiochemical, and catalytic qualities that directly stimulate plant growth, improve photosynthesis, and increase plant tolerance to biotic and abiotic stress in addition to their previously mentioned role as carriers. For instance, because of their numerous surface oxygen vacancies that fluctuate between two oxidation states (Ce^{3+} and Ce^{4+}), nanoscale CeO_2 particles are strong scavengers of reactive oxygen species (ROS) (Lowry et al., 2019).

Utilizing this antioxidant-enzyme-mimicking action can help plants respond more effectively to stress so they can survive. Additionally, carbon-based nanomaterials exhibit a number of noteworthy characteristics. Carbon dots, for instance, have self-fluorescence, which makes them suitable for tracking applications like stress monitoring, in contrast to conventional biochar. For application in

plants as sensors of signaling substances such as H_2O_2 , nitric oxide, and Ca^{2+} , carbon nanotubes have been produced. These and other remarkable qualities of NPs, like their biocompatibility and environmental friendliness, point to the viability of using them in agricultural productivity (Kah et al., 2019).

The ability of nanoparticles, which are essentially tiny metal-based matter particles, to function inside an experimental organism and make our desired organism more advantageous in terms of functioning in all aspects allows them to become an integrated system of different active principle consisting particles (Rocco et al., 1999).

For the past 50 years, future-oriented technology analysis or FTA, has been used to formulate different regulations, rights, and governance frameworks in the developing field of nanotechnology. The US and Germany have been forerunners in the creation and advancement of nanotechnology as compared to other nations (Baker et al., 2015).

Many factors influenced the development of nanotechnology. Technology forecasts and fundamental research and studies were among the main significant aspects. The development of this technology is the result of the enormous efforts of scientists, legislators, the media, and followers in the form of consumers of products focused on nanotechnology (EFSA, 2009). Four generations can be used to explain the development of nanotechnology: the first is a stage of passive nanoparticles (NPs) that work slowly; the second is a stage of active advanced nanoparticles; the third is technically oriented nanotechnology; and the fourth is a stage of integrating different fields (biotechnology, bioinformatics, pathology, etc.) to develop nanotechnology (Ruttkey-Nedecky et al., 2019).

6.1.1 Importance of Nanoparticle in Agricultural

Innovators in agriculture, nanoparticles provide revolutionary ways to improve resilience, sustainability, and crop productivity. These particles have a size that ranges from 1 to 100 nanometers and have special physicochemical characteristics that make them very useful in a variety of agricultural applications. The creation of improved fertilizers, which offer targeted and controlled nutrient release, greatly increases nutrient usage efficiency and lowers the impact on the environment, making it one of the most important applications for nanoparticles. These nanofertilizers minimize the demand for frequent treatments and lessen fertilizer discharge into water bodies by ensuring that vital nutrients are available to plants for extended periods of time (Singh et al., 2015). Furthermore, a major development in the control of weeds and pests is represented by nanopesticides and nanoherbicides. Through the utilization of nanoparticles' large surface area-to-volume ratios and their adaptable surface characteristics, these products can enhance the targeted and effective delivery of active substances, hence boosting their efficiency at reduced dosages. With this accuracy, the environmental impact of agricultural chemicals is lessened, and the hazards of overusing them such as degradation of soil and harm to

non-target species are reduced. Additionally, the control of plant diseases is greatly aided by nanoparticles. Their application in nanosensors makes it possible to identify plant diseases at the molecular level early on, allowing for prompt intervention and a decrease in crop losses. Furthermore, antimicrobial drugs can be delivered to sick plant tissues directly by means of nanoparticle engineering, guaranteeing efficient therapy with negligible environmental impact (Servin & White, 2016). The production of nanoscale fertilizers and growth promoters, which improve the soil's structure, retention of water, & nutrient availability, is facilitated by nanoparticles in soil management. These developments increase crop yields and encourage healthy plant growth. Moreover, the use of nanotechnology in agriculture goes so far as to improve plants' stress tolerance, making them more resilient to harsh environmental factors including salinity, drought, and high temperatures.

6.1.2 Overview of Nanoparticle in Plant Growth Promotion

Nanotechnology is a fast-growing scientific subject that combines several scientific fields to provide technological advancements and spark curiosity. The European Commission claims that one of the major enabling technologies that contributes to sustainable development is nanotechnology (Baker et al., 2019). Nano-agromaterials have proven to have a major influence on physiological processes and the rate of germination (Baker et al., 2017b). These nanoparticle-based particles pierce the dense seed wall and form pores that facilitate adequate water absorption, accelerating the germination process and boosting biomass production (Singh Sekhon, 2014). A prudent use of nano-agromaterials can boost agricultural output. The best qualities for promoting plant growth are directly linked to metabolic processes like photosynthesis, the creation of phytocomponents, the transduction of signals process, the production for pigments, the amount of chlorophyll, energy transfer, compatibility and effectiveness with a variety of crop productivity levels, and reduced phytotoxicity (Floros et al., 2010). It has been found that nanomaterials have strong micro-bicidal effects against a variety of harmful bacteria (Syed et al., 2017).

6.2 Objective

With an emphasis on how nanoparticles (NPs) can improve plant growth and development, this content aims to investigate the uses of nanotechnology in agriculture. It seeks to highlight the special qualities of types of nanoparticles that allow them to serve as smart and precise delivery vehicles for plant genetic material and agrochemicals. This chapter investigate the ways in which nanomaterials can increase nutrient uptake by offering vital elements in nano-forms that are easier for plant roots to absorb, resulting in better growth and development. Further,

objectively examines how nanomaterials affect the toxicity, mobility, and destiny of soil contaminants as well as their significance in various biotic and abiotic remediation techniques.

As “magic bullets,” these nanoparticles can deliver genes, herbicides, or nanopesticide fertilizers to particular plant cellular organelles for precise release. The toxicity of nanoparticles in plant systems is well understood, but less is known about the mechanisms by which they affect plant growth and development. Nanoparticles affect plant systems by promoting more investigation to clarify their physiological, biochemical, and molecular impacts (Elizabeth, 2019). Nanomaterials improve agrochemical efficiency, reduce environmental impact, and target specific plant sites to combat crop diseases. Despite these promising developments, nanotechnology in agriculture is still in its infancy, requiring further research to develop safe, biodegradable, and cost-effective materials. The content highlights the potential of nanotechnology to create a more sustainable and resilient agricultural system that improves food security (Xin et al., 2020). Herbicides, insecticides, and nutrients can be efficiently delivered to plant cells via nanoparticles. Although the toxicity of NPs to plants is well understood, the effects of NPs on plant development pathways have received less attention. To emphasize the necessity of investigating the physiological, biochemical, and molecular effects of nanoparticles on plants in order to maximize the advantages of nanoparticles for better plant growth and development (Siddiqui et al., 2015). This chapter provides a summary of recent advancements in the application of nanoparticles to promote plant growth, covering the kinds of nanoparticles employed, their modes of action, existing uses, and potential future results.

6.3 Application of Nanoparticles in Agriculture

Agriculture is changing as a result of nanotechnology's increased efficiency, sustainability, and productivity. With their controlled & directed nutrient release, nanofertilizers increase nutrient use efficiency while lessening their negative effects on the environment. With their exact distribution of active chemicals, nanopesticides and nanoherbicides maximize efficacy while reducing chemical usage & contaminants. Early plant disease diagnosis and real-time crop and soil health monitoring are made possible by nanosensors, which allows for prompt intervention. Furthermore, nanoparticles support plant growth, enhance soil structure also water retention, and aid in the development of drought-resistant crops. All things considered, nanotechnology presents creative answers to major agricultural problems and encourages sustainable farming methods. Recent advances in nanotechnology have raised hopes for applications in plant protection, on-site disease and pest monitoring, increasing crop output, and sustainable agricultural management through the use of nanofiltration for water (Mukhopadhyay & Rohatgi, 2014). Through the introduction of novel nano-formulations that can be utilized as nano-pesticides, nano-agrotechnology has the potential to deliver novel strategies. When compared to

traditional chemical pesticides, which have been frequently outlawed, these Nano pesticides have less of an adverse environmental impact (Aktar et al., 2009). To preserve the sustainability of the environment, nano-pesticides have been developed with a specific purpose in mind and are applied via a secure method. Nano-pesticides are utilized in a safe manner and have been specifically designed to protect the environment's sustainability (Baker et al., 2017a). The world's nutritional needs have been mostly met over the past 50 years thanks to a massive rise in agricultural productivity, particularly in cereals. One of the main factors increasing the crop output in this respect is the increased usage of chemical fertilizers.

The usage of chemical fertilizers has increased due to crop varieties that respond to fertilizer. However, because chemical fertilizers lose fertilizer through volatilization and leaching, which contaminates the environment and raises production costs, their poor usage efficiency limits the use of these fertilizers (FAO, 2017). By lowering production costs and increasing the quantity and quality of crops with increased nutrient usage efficiency, Nano fertilizers support sustainable agriculture. When compared to traditional fertilizers, Nano fertilizers had a median efficacy boost of 18–29%, according to a critical review of a dataset (Kah et al., 2018). Additionally, Nano fertilizers enhance plant metabolism and intake of nutrients by means of nonmetric apertures made possible by molecular carriers or nanostructure cuticle pores (Rico et al., 2011). Due to its exceptional qualities, colloidal Nano formulations have garnered a lot of interest for a variety of applications. These cutting-edge Nano formulation techniques improve pesticide system of administration and antifungal activity in the agricultural industry in a number of ways (Lv et al., 2018). The adjustment of drug penetration and optimal skin efficiency has been made possible by the integration of colloid Nano formulations in cosmetic goods. The food industry additionally employs this Nano formulation technology to increase food shelf life and enhance food preservation against the process about bio deterioration (da Silva Gündel et al., 2018). As a whole, some of the significant uses for nano-agroparticles may be found in Fig. 6.3.

6.4 The Destiny of Nanoparticles in Soil

The interaction between natural colloids & organic and mineral components as well as NMs could result in their partitioning into the solid & aqueous phases of the soil system (Darlington et al., 2009). NMs can change physically, chemically, or biologically when they come into contact with soil, based on their makeup and how they interact with different organic and inorganic soil constituents. The main physical process that happens naturally when NMs are added to the Earth's soil environment is aggregation. Aggregation decreases NMs' available surface area, which has an impact on how reactive they are. Additionally, as aggregate size increases, it will become less mobile in porous medium, which will alter NM reactivity & behaviour (Lowry et al., 2012). Aggregation can take two different forms: homoaggregation, which occurs between NMs, & heteroaggregation, which occurs between NMs along

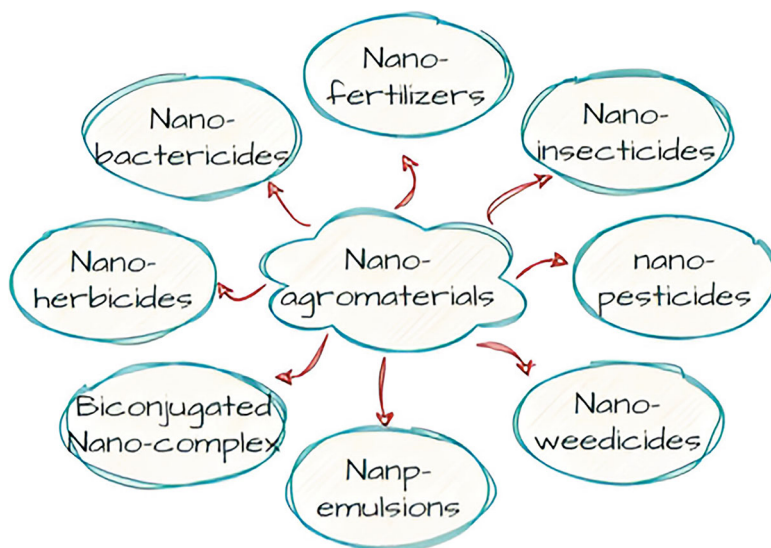


Fig. 6.3 Significant application of nano-agroparticle

with another particle in the atmosphere, such as natural colloids (Batley et al., 2013). Clay and iron minerals in particular are thought to be significant sinks for NMs in soil colloids & minerals. The importance of soil colloids was demonstrated by the quantification of NMs concentration in various particle-size fractions of soil, with a focus on water-dispersible colloids that preserved higher concentrations of MWCNTs and Ag nanoparticles (Makselon et al., 2018). Examined how the minerals kaolinite & montmorillonite found in soil clay affected the stability the MWCNTs stabilized by surfactants that were deposited in their presence. It has been proposed that the existence of these minerals will impair MWCNT stability and mobility in soils as well sediments (Han et al., 2008). Another important component that significantly influences the fate and behaviour of NMs is soil organic matter (SOM), mostly through adsorption and stabilization. Adsorption of SOM would cause NMs to become more surface-covered, reducing their active area of contact and perhaps reducing the effects of NMs (dong Li et al., 2008). Depending on its composition, soil organic matter may have conflicting impacts on the mobility and stability of NMs. SOM has been shown to hasten NM aggregation by bridging flocculation, on the one hand (Gao et al., 2019). However, by raising their electrostatic stability, it can make NMs more stable. A recent study showed a strong correlation between an increase in SOM and an increase in copper oxide NMs' solubility in soil, demonstrating the function of SOM in regulating these NMs' solubility (Zhang et al., 2011). The stabilizing impact was also concentration-dependent, with silver nanoparticles demonstrating greater stability under higher NM concentration when organic matter was present. It was recently proposed that, in addition to the total SOM contents, the heterogeneity among SOM fractions should

additionally be taken into account (Klitzke et al., 2015). They examined the effects of two main SOM fractions on hydroxyapatite nanoparticle mobility that was impeded by organic matter linked with minerals as a result of mechanical straining and surface deposition. However, by enhancing the electrostatic repulsion between the hydroxyapatite nanoparticles with the soil surfaces, dissolving organic matter increased the mobility of the nanoparticles (Xu et al., 2019).

6.5 Smart Delivery Options Assisted by Nanoparticles: A Novel Approach to Sustainable Agriculture

One of the most important technologies during the twenty-first century, nanotechnology promises to improve agricultural practices and promote sustainable development by enhancing management and conservation strategies and minimizing input waste (Jampílek & Král'ová, 2015). Agrochemical & organic molecule delivery techniques, which include the transfer of DNA or oligonucleotides within plant cells, are crucial components of precision farming & sustainable agricultural output (Joga et al., 2016). The recent development of nanotechnology-based production of herbicides, insecticides, and slow- or controlled-release fertilizers have therefore drawn particular interest in agriculture farming as an effort to assure environmentally benign agricultural practices. Nanotechnology has gradually evolved from laboratory-based experimental experiments to real-world applications over time. By releasing precisely the right amount of essential and sufficient agrochemicals throughout time, controlled delivery systems seek to maximize biological competency while minimizing loss and adverse consequences (Shojaei et al., 2019). The benefits of efficient pesticide delivery are provided by nanoparticles because of their enormous surface area, ease of attachment, and quick mass transfer. Despite these reasons, agrochemicals include micronic or submicronic particles via a variety of methods, including trapping into the nano-matrix of active substances, ionic surface attachments, absorption, & capsulation (Pandey, 2018). For instance, potassium nitrate capsules made of graphene oxide films significantly extend the fertilizer release process, and massive amounts production of this kind of formulation appears to be feasible at a relatively low cost (Zhang et al., 2014). The benefits of efficient pesticide delivery are provided by nanoparticles because of their enormous surface area, ease of attachment, and quick mass transfer. Despite these reasons, agrochemicals include micronic or submicronic particles via a variety of methods, including trapping into the nano-matrix of active substances, ionic surface attachments, absorption, & capsulation. For instance, potassium nitrate capsules made of graphene oxide films significantly extend the fertilizer release process, and massive amounts production of this kind of formulation appears to be feasible at a relatively low cost (Lyons, 2010). In addition to its uses in agriculture, the merging of nanotechnology using biotechnology offers novel molecular transporter tools that can be used to change genes as well as create entirely new creatures. In Nano

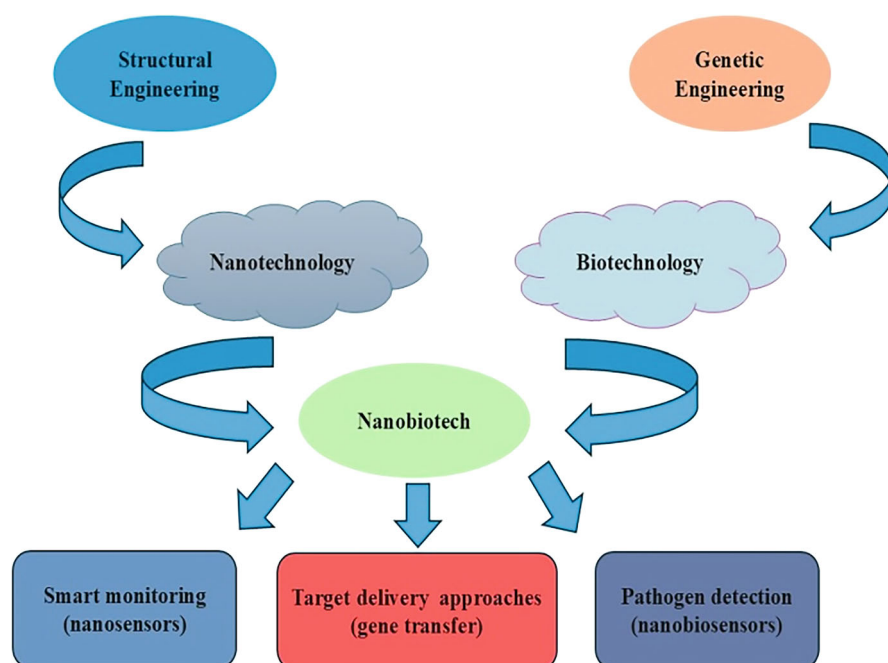


Fig. 6.4 An introduction of nano biotechnology: the field encompasses knowledge of genetic and structural engineering, as well as the convergence of nanotechnology and biotechnology

biotechnologies, for example, foreign DNA and compounds that aid in modifying target genes are carried by nanoparticles, Nano capsules, & Nano fibres. Viral gene delivery vectors encounter many difficulties while delivering genetic materials, including a restricted host range, a restricted size for inserted genetic material, cell membrane transit, and the issue of nucleus trafficking (Ghormade et al., 2011). On the other hand, new developments in Nano biotechnology give scientists more chances to fully substitute the genetic information of one species with that of another. A new chapter in genetic engineering has been initiated by recent developments in the targeted delivery of CRISPR/Cas9 single guide RNA (sgRNA) via nanomaterials. The CRISPR/Cas9 system, which consists of Cas proteins and CRISPR repeat-spacer arrays, is an RNA-directed defence mechanism found in prokaryotes that has been effectively applied to plant genome editing (Miller et al., 2017). Overview of Nano biotechnology explains in Fig. 6.4.

6.6 Nanomaterials for Plant Protection Using Pesticides

The use of various chemically generated items, particularly pesticides, has drawn major concern from scientific studies and regulatory organizations around the world. These substances are really concerning. For instance, two neonicotinoids that are

extremely harmful to bees and the aquatic environment are clothionidin and thiomethoxam (Krupke et al., 2012). Many organicphosphorous pesticides (OPPs) are extremely harmful because they build up in the body's adipose tissues and produce biomagnification in species at greater tropical levels, upsetting the ecology and food chain (Baker et al., 2017b). Certain OPPs have the ability to seep into water bodies and taint potable water (Baker et al., 2013). Glyphosate, a widely used OPP, was recently discovered to be hazardous to people (Guyton et al., 2015). Breast milk has been found to contain some of the OPPs, which can enter the human diet. An alarming number of poisonings occur worldwide each year, and the severity of OPPs is growing at an alarming rate. The effects of OPPs range from mild to significant and include cancer, neurological effects, Parkinson's disease, respiratory diseases, fatal diseases, genetic disorders, infertility, and diabetes. Various strategies have been used, such as the manufacture of biopesticides and the use of environmentally friendly agricultural chemicals, to counteract the negative impacts of pesticides. Because of their inadequate efficacy and inability to meet market demand, these environmentally benign insecticides have compelled scientific groups to devise other approaches. Therefore, the introduction of pesticides based on nanomaterials and having a biological origin can mitigate the drawbacks of the pesticides that are now in use. The insecticidal activity of nanostructured aluminium against the important food pests *Sitophilus oryzae* and *Rhyzopertha dominica* was revealed in a 2009 study by (Stadler et al., 2010). Comparing the activity of nano-aluminum to commercially available insecticidal dust, the latter showed lower fatality rates. In a similar vein, porous hollow silica nanoparticles were synthesized to produce a control pesticide delivery system, including validamycin. According (Liu et al., 2006) the temperature and pH of the dissolution media have a major impact on the activity of nanoparticles and their rate of release. Likewise, when silver and silver-zinc combination nanoparticles were tested against *Aphis nerii* Boyer de Fonscolombe, the mortality LC50 values were determined to be 424.67 and 539.46 mg/mL, respect (Rouhani et al., 2013).

6.7 Recent Developments in the Use of Nanoparticles in Plant Growth Promotion

Smart agriculture is the result of the use of nanotechnology in the form of nanopesticides, nanofertilizers, and nanosensors into traditional agricultural operations. According to reports, using nanoparticles as an agricultural input targets certain species, delivers chemicals precisely where they are needed, and doesn't harm non-targeted ones (Chhipa, 2019). The agriculture community is currently dealing with a wide range of challenges, such as stagnant yield, pest-related crop destruction, loss of soil fertility, inadequate water, fluctuating climatic conditions, and soil contamination that has resulted in severe loss (Pouratashi & Iravani, 2012). To address these issues, innovative approaches and rational design are crucial. Nano-

agroparticles are nano-sized particles that are designed to alleviate the problems related to the agriculture sector (Parisi et al., 2015). These nanoparticles can effectively function as fungicides, insecticides, herbicides, pesticides, and plant growth-promoting factors.

6.7.1 *Types of Nanoparticles Used*

6.7.1.1 Nanoparticles of Silver

These nanoparticles, which have a size range of 10–20 nm, mostly consist of silver ions. Within biological systems, these particles exhibit significant activity and efficacy. These can be produced using a variety of techniques, including chemical, biological, and physical ones. Silver nanoparticles have been applied to combat a range of pathogenic microorganisms. For instance, silver nanoparticles have been shown to heal spot blotch illness. Silver nanoparticles can also be used to break seed dormancy, boost the vigor index of seeds, and raise the fresh weight of (Hojjat & Hojjat, 2015). Silver nanoparticles are environmentally benign and simple to synthesis.

6.7.1.2 Nanoparticles of Zinc Oxide

Due to zinc's limited availability and alkaline pH in calcium carbonate-enriched soils, both plants and soils typically suffer from a zinc deficit (Alloway, 2009). Alternatives such as zinc sulphate fertilizer are used to lessen this, however even in these cases, plants still lack zinc. Because of their huge surface area and compact size, zinc oxide nanoparticles are the most effective way to help plants that are deficient in zinc. The efficiency of the zinc oxide nanoparticles is high because of their small size of 100 nm (Xie et al., 2011). Zinc sulfate heptahydrate is dissolved in water to create these NPs. In addition, the intended biological entity such as since the bioactive extract is extracted using both plants and animals. Either water or ethanol is used to make the extract. After mixing the two prepared solutions at the proper pH, the desired zinc oxide nanoparticles are produced. These nanoparticles may offer a low-cost, environmentally friendly, and long-lasting solution to a number of plant issues, including pathogenic invasions and zinc deficiencies.

6.7.1.3 Nanoparticles of Titanium Dioxide

Titanium dioxide nanoparticles, or TiO₂ NPs, are widely produced and utilized worldwide, with sizes ranging from 5 to 30 nm (Xie et al., 2011). Due of titanium's capacity as a photocatalyst, these nanoparticles are in high demand. These are employed in pigment formulations as a result of this characteristic (Sang et al.,

2014). These nanoparticles help plants develop and perform photosynthesis. According to Abdel Latef et al. (2018), broad beans, a leguminous crop that grows widely, had their soil salinity reduced by titanium dioxide nanoparticles ($n\text{TiO}_2$). Additionally, it is sprayed on leaves or roots at extremely low concentrations to promote the activity of plant growth enzymes, enhance nutrient uptake, promote stress tolerance, and improve crop output and quality at levels by photosynthesis of chlorophyll content. TiO_2 deposits within plant bodies kill pests as well, making it an effective pesticide.

6.7.1.4 Iron Dioxide Particles

Due to its ability to replace conventional, ineffective Fe fertilizers, iron oxide nanoparticles, or $\text{Fe}_2\text{O}_3\text{NPs}$, are extremely important oxide nanomaterials used extensively in agriculture. In addition, it plays a crucial role in water treatment, biomedicine, catalysis, and other areas (Singh et al., 2016). Iron-NPs are produced by chemical, biological, or mechanochemical processes, and they typically have a size of $<10\text{--}20\text{ nm}$. They also display the unique kind of magnetism. They can take on a variety of forms, including self-orienting flowers, spheres, cubes, and rods. Although plants and other living things can only absorb iron in the form of Fe^{2+} , it is naturally abundant in Fe^{3+} . Fe helps mediate a number of physiological responses in plants, including the production of leghemoglobin in nodules, chlorophyll synthesis, redox reaction, respiration, etc. However, just in the necessary amount as excess or insufficiency are both detrimental. A variety of crops frequently have a Fe deficit. According to *Arachis hypogaea*, or peanuts, are extremely sensitive to iron deficiency (Sánchez-Alcalá et al., 2014). Research findings indicate that iron oxide nanoparticles have a good impact on plant development and productivity, as demonstrated by the peanut, soybean, and wheat crops (Sheykhabglou et al., 2010).

6.7.1.5 Cu-Based Nanoparticles

Copper (Cu) is an excellent material for the sustainable preparation of Cu-based nanoparticles (Cu-NPs) due to its high abundance and inexpensive cost. Cu's transitional qualities open up a wide range of potential applications, including water treatment, solar cells, optics, and sensors (Eivazihollagh et al., 2018). Cu-NPs are agglomeration, hemispheric, and cube-shaped particles with a size range of $42\text{--}146\text{ nm}$. Cu-based NPs have been identified as promising agro-fungicides and have demonstrated efficacy against a variety of phytopathogens, including *Penicillium italicum*, *Fusarium* sp., *Phoma destructiva*, *C. lunata*, *A. alternate*, *F. oxysporum*, *P. digitatum*, and *R. solani* (Pariona et al., 2019). Cu_2O NPs have been described as agro-fungicides for the control of *Phytophthora infestans*, a major plant disease-causing agent. Curiously, Cu-NPs cause oxidative stress, and depending on the type of fungus, they may function differently.

6.7.2 *Mechanisms of Action*

By addressing issues with ineffective, bulky, and non-targeted agro-producers and protectors (fertilizers, growth promoters, pesticides, herbicides, etc.), nanoparticle-based weedicides, fungicides, and growth activating factors are now applied to crops based on source and mode of action (Parisi et al., 2015). The fundamental functions and properties of bio-nano-hybrid molecules are contingent upon the physicochemical and biochemical characteristics of both the nanoparticles and the bioactive molecules integrated within the hybrids. The performance of bio-nano-hybrid particles is variable and tailored to meet the needs of consumers and farmers. However, the efficacy of nanoparticles (NPs) is contingent upon their interactions with the substrate to which they are applied. The impact and effectiveness of NPs are directly proportional to their uptake and distribution within crops.

Although cell walls and coatings often enclose plant organs, NPs have the ability to breach these barriers. Size is the primary criterion for NP penetration into plant tissues and cells. According to reports, plants permitted NPs with a size of up to 40–50 nm for smooth translocation and penetration (Sabo-Attwood et al., 2012). Another important aspect impacting absorption and accumulation by plant tissues is the shape, chemical content, and coated materials. Furthermore, Larue et al. have demonstrated how plant species variety affects NPs' ability to penetrate plants. Moreover, NP absorption and activity are influenced by soil characteristics, plant microbiota, and environmental factors. Once NPs have penetrated the plant's surface, they modify either apoplast or symplast transportation to pass through tissues. NPs go across the plasma membrane's extracellular space during apoplast transit to reach plant cell vasculature (Sattelmacher, 2001). Through radial migration, NPs can enter the plant's vascular system and the central cylinder of roots thanks to apoplast transportation. Transport of NPs via plasmodesmata and cell sieves occurs during symplastic motions. Other nutrients and water molecules are also beneficial in these movements.

The first obstacle for NPs using foliar spray is getting beyond the leaf cuticle layer. In order to accomplish this, NPs diffuse the cuticle waxes and enter the cuticle/stomata pores via the hydrophobic or lipophilic pathway (Schönherr, 2002). Owing to the favourable stomata pore diameter of approximately 10 nm, this is the most practical route for NPs to penetrate when applied topically. Furthermore, the most promising approach for its effective use is to think about applying nano-agroparticles in combination—that is, to the soil and to foliar absorption. Because a plant's ability to expand and bear fruit is determined by its ability to support healthy root growth and development after it has seeded. Additionally, the root is the best route for absorbing nutrients from the earth. Therefore, the use of agro-nanoparticles allows for the continuous delivery of fertilizer and other nutrients to the roots and leaves in accordance with plant requirement. A significant part of NP penetration, absorption, and translocation in plants and agricultural crops is also played by endocytosis, pore formation, carrier proteins, ion channels, and other processes.

6.8 Conclusion

In agriculture, the use of nanotechnology as nanopesticides, nanofertilizers, and nanosensors has greatly demonstrated its applicability in crop production and plant growth in a sustainable way. Their site-specific delivery and controlled release at the nanoscale made them effective instruments for intelligent agricultural systems. Within specific concentration ranges, several metal and metal oxide nanoparticles favourably boosted plant growth, biomass, and seed germination rates as well as root and shoot elongation. But there are still a lot of unexplored areas in nanotechnology, and it's urgent to find them. Further investigation into nanotechnology is necessary to comprehend the molecular interactions between polymers and nutraceuticals, as well as how these interactions affect the delivery of food sector products.

The toxicity of nanoparticles is one of the main obstacles. Therefore, several logical methods are being developed to counteract the harmful impacts. One such tactic, which is one of the environmentally benign methods for synthesizing nanoparticles, is the utilization of biological entities or their products. Additionally, encasing and bioconjugating nanoparticles with bioactive compounds is a promising field that reduces the possibility of toxicity. Thus, diverse experts should work together to build biomimetic nanoparticles and evaluate them in the agriculture sector in order to successfully use and commercialize nanomaterials.

References

- Abdel Latef, A. A. H., Srivastava, A. K., El-sadek, M. S. A., Kordrostami, M., & Tran, L. P. (2018). Titanium dioxide nanoparticles improve growth and enhance tolerance of broad bean plants under saline soil conditions. *Land Degradation & Development*, 29(4), 1065–1073.
- Achari, G. A., & Kowshik, M. (2018). Recent developments on nanotechnology in agriculture: Plant mineral nutrition, health, and interactions with soil microflora [Review-article]. *Journal of Agricultural and Food Chemistry*, 66(33), 8647–8661. <https://doi.org/10.1021/acs.jafc.8b00691>
- Agathokleous, E., Feng, Z. Z., Iavicoli, I., & Calabrese, E. J. (2020). Nano-pesticides: A great challenge for biodiversity? The need for a broader perspective. *Nano Today*, 30, 100808. <https://doi.org/10.1016/j.nantod.2019.100808>
- Aktar, W., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticides use in agriculture: Their benefits and hazards. *Interdisciplinary Toxicology*, 2(1), 1–12. <https://doi.org/10.2478/v10102-009-0001-7>
- Alloway, B. J. (2009). Soil factors associated with zinc deficiency in crops and humans. *Environmental Geochemistry and Health*, 31(5), 537–548.
- Baker, S., Harini, B. P., Rakshith, D., & Satish, S. (2013). Marine microbes: Invisible nanofactories. *Journal of Pharmacy Research*, 6(3), 383–388. <https://doi.org/10.1016/j.jopr.2013.03.001>
- Baker, S., Mohan Kumar, K., Santosh, P., Rakshith, D., & Satish, S. (2015). Extracellular synthesis of silver nanoparticles by novel pseudomonas veronii AS41G inhabiting Annona squamosa L. and their bactericidal activity. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 136, 1434–1440. <https://doi.org/10.1016/j.saa.2014.10.033>

- Baker, S., Pasha, A., & Satish, S. (2017a). Biogenic nanoparticles bearing antibacterial activity and their synergistic effect with broad spectrum antibiotics: Emerging strategy to combat drug resistant pathogens. *Saudi Pharmaceutical Journal*, 25(1), 44–51. <https://doi.org/10.1016/j.jsps.2015.06.011>
- Baker, S., Volova, T., Prudnikova, S. V., Satish, S., & Nagendra-Prasad, M. N. (2017b). Nanoagroparticles emerging trends and future prospect in modern agriculture system. *Environmental Toxicology and Pharmacology*, 53, 10–17. <https://doi.org/10.1016/j.etap.2017.04.012>
- Baker, S., Satish, S., Prasad, N., & Chouhan, R. S. (2019). Nano-agromaterials: Influence on plant growth and crop protection. In *Industrial applications of nanomaterials*. Elsevier. <https://doi.org/10.1016/B978-0-12-815749-7.00012-8>
- Batley, G. E., Kirby, J. K., & McLaughlin, M. J. (2013). Fate and risks of nanomaterials in aquatic and terrestrial environments. *Accounts of Chemical Research*, 46(3), 854–862. <https://doi.org/10.1021/ar2003368>
- Chhipa, H. (2019). Applications of nanotechnology in agriculture. In *Methods in microbiology* (Vol. 46, 1st ed.). Elsevier Ltd. <https://doi.org/10.1016/bs.mim.2019.01.002>
- da Silva Gündel, S., Velho, M. C., Diefenthaler, M. K., Favarin, F. R., Copetti, P. M., de Oliveira Fogaça, A., Klein, B., Wagner, R., Gündel, A., Sagrillo, M. R., & Ourique, A. F. (2018). Basil oil-nanoemulsions: Development, cytotoxicity and evaluation of antioxidant and antimicrobial potential. *Journal of Drug Delivery Science and Technology*, 46, 378–383. <https://doi.org/10.1016/j.jddst.2018.05.038>
- Darlington, T. K., Neigh, A. M., Spencer, M. T., Nguyen, O. T., & Oldenburg, S. J. (2009). Nanoparticle characteristics affecting environmental fate and transport through soil. *Environmental Toxicology and Chemistry*, 28(6), 1191–1199. <https://doi.org/10.1897/08-341.1>
- de Lima, P. H. C., Antunes, D. R., Forini, M. M. d. L., Pontes, M. d. S., Mattos, B. D., & Grillo, R. (2021). Recent advances on lignocellulosic-based nanopesticides for agricultural applications. *Frontiers in Nanotechnology*, 3, 1–9. <https://doi.org/10.3389/fnano.2021.809329>
- EFSA. (2009). The potential risks arising from nanoscience and nanotechnologies on food and feed safety. *EFSA Journal*, 7(3), 958.
- Eivazihollagh, A., Norgren, M., Dahlström, C., & Edlund, H. (2018). Controlled synthesis of Cu and Cu₂O nps and incorporation of octahedral Cu₂O nps in cellulose II films. *Nanomaterials*, 8(4), 1–11. <https://doi.org/10.3390/nano8040238>
- Elizabeth, A. (2019). Application of nanotechnology in agriculture. *International Journal of Pure & Applied Bioscience*, 7(2), 131–139. <https://doi.org/10.18782/2320-7051.6493>
- Floros, J. D., Newsome, R., Fisher, W., Barbosa-Cánovas, G. V., Chen, H., Dunne, C. P., German, J. B., Hall, R. L., Heldman, D. R., Karwe, M. V., Knabel, S. J., Labuza, T. P., Lund, D. B., Newell-McGloughlin, M., Robinson, J. L., Sebranek, J. G., Shewfelt, R. L., Tracy, W. F., Weaver, C. M., & Ziegler, G. R. (2010). Feeding the world today and tomorrow: The importance of food science and technology. *Comprehensive Reviews in Food Science and Food Safety*, 9(5), 572–599. <https://doi.org/10.1111/j.1541-4337.2010.00127.x>
- Food and Agriculture Organization of the United Nations. (2017). *The future of food and agriculture: Trends and challenges*. FAO.
- Gao, X., Rodrigues, S. M., Spielman-Sun, E., Lopes, S., Rodrigues, S., Zhang, Y., Avellan, A., Duarte, R. M. B. O., Duarte, A., Casman, E. A., & Lowry, G. V. (2019). Effect of soil organic matter, soil pH, and moisture content on solubility and dissolution rate of CuO NPs in soil. *Environmental Science & Technology*, 53(9), 4959–4967. <https://doi.org/10.1021/acs.est.8b07243>
- Ghormade, V., Deshpande, M. V., & Paknikar, K. M. (2011). Perspectives for nano-biotechnology enabled protection and nutrition of plants. *Biotechnology Advances*, 29(6), 792–803. <https://doi.org/10.1016/j.biotechadv.2011.06.007>
- Giraldo, J. P., Wu, H., Newkirk, G. M., & Kruss, S. (2019). Nanobiotechnology approaches for engineering smart plant sensors. *Nature Nanotechnology*, 14(6), 541–553. <https://doi.org/10.1038/s41565-019-0470-6>

- Guyton, K. Z., Loomis, D., Grosse, Y., El Ghissassi, F., Benbrahim-Tallaa, L., Guha, N., Scoccianti, C., Mattock, H., & Straif, K. (2015). Carcinogenicity of tetrachlorvinphos, parathion, malathion, diazinon, and glyphosate. *The Lancet Oncology*, 16(5), 490–491. [https://doi.org/10.1016/S1470-2045\(15\)70134-8](https://doi.org/10.1016/S1470-2045(15)70134-8)
- Han, Z., Zhang, F., Lin, D., & Xing, B. (2008). Clay minerals affect the stability of surfactant-facilitated carbon nanotube suspensions. *Environmental Science & Technology*, 42(18), 6869–6875. <https://doi.org/10.1021/es801150j>
- Hojjat, S. S., & Hojjat, H. (2015). Effect of nano silver on seed germination and seedling growth in fenugreek seed. *ETP International Journal of Food Engineering*, 1(2), 10.18178/ijfe.1.2.106-110.
- Jampřílek, J., & Král'ová, K. (2015). Application of nanotechnology in agriculture and food industry, its prospects and risks. *Ecological Chemistry and Engineering S*, 22(3), 321–361. <https://doi.org/10.1515/eces-2015-0018>
- Joga, M. R., Zotti, M. J., Smaghe, G., & Christiaens, O. (2016). RNAi efficiency, systemic properties, and novel delivery methods for pest insect control: What we know so far. *Frontiers in Physiology*, 7, 1–14. <https://doi.org/10.3389/fphys.2016.00553>
- Kah, M., Kookana, R. S., Gogos, A., & Bucheli, T. D. (2018). A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nature Nanotechnology*, 13(8), 677–684. <https://doi.org/10.1038/s41565-018-0131-1>
- Kah, M., Tufenkji, N., & White, J. C. (2019). Nano-enabled strategies to enhance crop nutrition and protection. *Nature Nanotechnology*, 14(6), 532–540. <https://doi.org/10.1038/s41565-019-0439-5>
- Klitze, S., Metreveli, G., Peters, A., Schaumann, G. E., & Lang, F. (2015). The fate of silver nanoparticles in soil solution—Sorption of solutes and aggregation. *Science of the Total Environment*, 535, 54–60. <https://doi.org/10.1016/j.scitotenv.2014.10.108>
- Krupke, C. H., Hunt, G. J., Eitzer, B. D., Andino, G., & Given, K. (2012). Multiple routes of pesticide exposure for honey bees living near agricultural fields. *PLoS One*, 7(1), e29268.
- Li, D., Lyon, D. Y., Li, Q., & Alvarez, P. J. J. (2008). Effect of soil sorption etc on the antimicrobial activity of fullerene. *Environmental Toxicology and Chemistry*, 27(9), 1888–1894.
- Li, T., Lü, S., Wang, Z., Huang, M., Yan, J., & Liu, M. (2021). Lignin-based nanoparticles for recovery and separation of phosphate and reused as renewable magnetic fertilizers. *Science of the Total Environment*, 765, 142745. <https://doi.org/10.1016/j.scitotenv.2020.142745>
- Liu, F., Wen, L. X., Li, Z. Z., Yu, W., Sun, H. Y., & Chen, J. F. (2006). Porous hollow silica nanoparticles as controlled delivery system for water-soluble pesticide. *Materials Research Bulletin*, 41(12), 2268–2275. <https://doi.org/10.1016/j.materresbull.2006.04.014>
- Lowry, G. V., Gregory, K. B., Apte, S. C., & Lead, J. R. (2012). Transformations of nanomaterials in the environment. *Environmental Science & Technology*, 46(13), 6893–6899. <https://doi.org/10.1021/es300839e>
- Lowry, G. V., Avellan, A., & Gilbertson, L. M. (2019). Opportunities and challenges for nanotechnology in the agri-tech revolution. *Nature Nanotechnology*, 14(6), 517–522. <https://doi.org/10.1038/s41565-019-0461-7>
- Lv, M., Liu, Y., Geng, J., Kou, X., Xin, Z., & Yang, D. (2018). Engineering nanomaterials-based biosensors for food safety detection. *Biosensors and Bioelectronics*, 106, 122–128. <https://doi.org/10.1016/j.bios.2018.01.049>
- Lyons, K. (2010). Nanotechnology: Transforming food and the environment. *Food First Backgrounder*, 16(1), 1–4.
- Makselon, J., Siebers, N., Meier, F., Vereecken, H., & Klumpp, E. (2018). Role of rain intensity and soil colloids in the retention of surfactant-stabilized silver nanoparticles in soil. *Environmental Pollution*, 238, 1027–1034. <https://doi.org/10.1016/j.envpol.2018.02.025>
- Miller, J. B., Zhang, S., Kos, P., Xiong, H., Zhou, K., Perelman, S. S., Zhu, H., & Siegwart, D. J. (2017). Non-viral CRISPR/Cas gene editing in vitro and in vivo enabled by synthetic nanoparticle co-delivery of Cas9 mRNA and sgRNA. *Angewandte Chemie – International Edition*, 56(4), 1059–1063. <https://doi.org/10.1002/anie.201610209>

- Mittal, D., Kaur, G., Singh, P., Yadav, K., & Ali, S. A. (2020). Nanoparticle-based sustainable agriculture and food science: Recent advances and future outlook. *Frontiers in Nanotechnology*, 2, 579954. <https://doi.org/10.3389/fnano.2020.579954>
- Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature*, 490(7419), 254–257. <https://doi.org/10.1038/nature11420>
- Mukhopadhyay, S., & Rohatgi, R. (2014). G-protein-coupled receptors, hedgehog signaling and primary cilia. *Seminars in Cell and Developmental Biology*, 33, 63–72. <https://doi.org/10.1016/j.semcdb.2014.05.002>
- Okolie, J. A., Nanda, S., Dalai, A. K., & Kozinski, J. A. (2021). Chemistry and specialty industrial applications of lignocellulosic biomass. *Waste and Biomass Valorization*, 12(5), 2145–2169. <https://doi.org/10.1007/s12649-020-01123-0>
- Pandey, G. (2018). Challenges and future prospects of agri-nanotechnology for sustainable agriculture in India. *Environmental Technology & Innovation*, 11, 299–307. <https://doi.org/10.1016/j.eti.2018.06.012>
- Pariona, N., Mtz-Enriquez, A. I., Sánchez-Rangel, D., Carrión, G., Paraguay-Delgado, F., & Rosas-Saito, G. (2019). Green-synthesized copper nanoparticles as a potential antifungal against plant pathogens. *RSC Advances*, 9(33), 18835–18843. <https://doi.org/10.1039/c9ra03110c>
- Parisi, C., Viganì, M., & Rodríguez-Cerezo, E. (2015). Agricultural nanotechnologies: What are the current possibilities? *Nano Today*, 10(2), 124–127. <https://doi.org/10.1016/j.nantod.2014.09.009>
- Pouratashi, M., & Irvani, H. (2012). Farmers' knowledge of integrated pest management and learning style preferences: Implications for information delivery. *International Journal of Pest Management*, 58(4), 347–353. <https://doi.org/10.1080/09670874.2012.724468>
- Raliya, R., Saharan, V., Dimkpa, C., & Biswas, P. (2018). Nanofertilizer for precision and sustainable agriculture: Current state and future perspectives. *Journal of Agricultural and Food Chemistry*, 66(26), 6487–6503. <https://doi.org/10.1021/acs.jafc.7b02178>
- Rico, C. M., Majumdar, S., Duarte-Gardea, M., Peralta-Videa, J. R., & Gardea-Torresdey, J. L. (2011). Interaction of nanoparticles with edible plants and their possible implications in the food chain. *Journal of Agricultural and Food Chemistry*, 59(8), 3485–3498. <https://doi.org/10.1021/jf104517j>
- Rocco, M. C., William, R. S., & Alivisatos, P. (1999). *Nanotechnology research directions: IWGN workshop report*. National Science and Technology Council.
- Rodrigues, S. M., Demokritou, P., Dokoozlian, N., Hendren, C. O., Karn, B., Mauter, M. S., Sadik, O. A., Safarpour, M., Unrine, J. M., Viers, J., Welle, P., White, J. C., Wiesner, M. R., & Lowry, G. V. (2017). Nanotechnology for sustainable food production: Promising opportunities and scientific challenges. *Environmental Science: Nano*, 4(4), 767–781. <https://doi.org/10.1039/c6en00573j>
- Rouhani, M., Samih, M. A., & Kalantari, S. (2013). Insecticidal effect of silica and silver nanoparticles on the cowpea seed beetle, *Callosobruchus maculatus* F.(Col.: Bruchidae). *Journal of Entomological Research*, 4, 297–305.
- Ruttkay-Nedecky, B., Skalickova, S., Kepinska, M., Cihalova, K., Docekalova, M., Stankova, M., Uhlirova, D., Fernandez, C., Sochor, J., & Milnerowicz, H. (2019). Development of new silver nanoparticles suitable for materials with antimicrobial properties. *Journal of Nanoscience and Nanotechnology*, 19(5), 2762–2769.
- Sabo-Attwood, T., Unrine, J. M., Stone, J. W., Murphy, C. J., Ghoshroy, S., Blom, D., Bertsch, P. M., & Newman, L. A. (2012). Uptake, distribution and toxicity of gold nanoparticles in tobacco (*Nicotiana xanthi*) seedlings. *Nanotoxicology*, 6(4), 353–360.
- Sánchez-Alcalá, I., del Campillo, M. d. C., Barrón, V., & Torrent, J. (2014). Evaluation of preflooding effects on iron extractability and phytoavailability in highly calcareous soil in containers. *Journal of Plant Nutrition and Soil Science*, 177(2), 150–158.
- Sang, L., Zhao, Y., & Burda, C. (2014). TiO₂ nanoparticles as functional building blocks. *Chemical Reviews*, 114(19), 9283–9318.

- Sattelmacher, B. (2001). The apoplast and its significance for plant mineral nutrition. *New Phytologist*, 149(2), 167–192.
- Schönherr, J. (2002). A mechanistic analysis of penetration of glyphosate salts across stomatal cuticular membranes. *Pest Management Science: Formerly Pesticide Science*, 58(4), 343–351.
- Servin, A. D., & White, J. C. (2016). Nanotechnology in agriculture: Next steps for understanding engineered nanoparticle exposure and risk. *NanoImpact*, 1, 9–12. <https://doi.org/10.1016/j.impact.2015.12.002>
- Shabala, S., Bose, J., & Hedrich, R. (2014). Salt bladders: Do they matter? *Trends in Plant Science*, 19(11), 687–691. <https://doi.org/10.1016/j.tplants.2014.09.001>
- Sheykhabaglou, R., Sedghi, M., Shishevan, M. T., & Sharifi, R. S. (2010). Effects of nano-iron oxide particles on agronomic traits of soybean. *Notulae Scientia Biologicae*, 2(2), 112–113.
- Shojaei, T. R., Salleh, M. A. M., Tabatabaei, M., Mobli, H., Aghbashlo, M., Rashid, S. A., & Tan, T. (2019). Applications of nanotechnology and carbon nanoparticles in agriculture. In *Synthesis, technology and applications of carbon nanomaterials* (pp. 247–277). Elsevier.
- Siddiqui, M. H., Al-Wahaibi, M. H., Mohammad, F., & Al-Khaishany, M. Y. (2015). Role of nanoparticles in plants. In M. H. Siddiqui, F. Mohammad, & M. Al-Wahaibi (Eds.), *Nanotechnology and plant sciences: Nanoparticles and their impact on plants* (pp. 19–35). Springer International Publishing. https://doi.org/10.1007/978-3-319-14502-0_2
- Singh Sekhon, B. (2014). Nanotechnology in agri-food production: An overview. *Nanotechnology, Science and Applications*, 7(2), 31–53. <https://doi.org/10.2147/NSA.S39406>
- Singh, A., Singh, N. B., Hussain, I., Singh, H., & Singh, S. C. (2015). Plant-nanoparticle interaction: An approach to improve agricultural practices and plant productivity. *International Journal of Pharmaceutical Science Invention*, 4(8), 25–40.
- Singh, R. P., Manchanda, G., Singh, R. N., Srivastava, A. K., & Dubey, R. C. (2016). Selection of alkalotolerant and symbiotically efficient chickpea nodulating rhizobia from North-West Indo Gangetic Plains. *Journal of Basic Microbiology*, 56(1), 14–25.
- Stadler, T., Butler, M., & Weaver, D. K. (2010). Novel use of nanostructured alumina as an insecticide. *Pest Management Science: Formerly Pesticide Science*, 66(6), 577–579.
- Syed, B., Nagendra, N. P., Kumar, M. K., Dhananjaya, B. L., & Satish, S. (2017). Endo-symbiont mediated synthesis of gold nanobactericides and their activity against human pathogenic bacteria. *Environmental Toxicology and Pharmacology*, 52, 143–149. <https://doi.org/10.1016/j.etap.2017.03.016>
- Toumey, C. (2008). Reading Feynman into nanotechnology: A text for a new science. *Techné: Research in Philosophy and Technology*, 12(3), 133–168.
- Xie, Y., He, Y., Irwin, P. L., Jin, T., & Shi, X. (2011). Antibacterial activity and mechanism of action of zinc oxide nanoparticles against *Campylobacter jejuni*. *Applied and Environmental Microbiology*, 77(7), 2325–2331.
- Xin, X., Judy, J. D., Sumerlin, B. B., & He, Z. (2020). Nano-enabled agriculture: From nanoparticles to smart nanodelivery systems. *Environmental Chemistry*, 17(6), 413–425. <https://doi.org/10.1071/EN19254>
- Xu, S., Chen, X., & Zhuang, J. (2019). Opposite influences of mineral-associated and dissolved organic matter on the transport of hydroxyapatite nanoparticles through soil and aggregates. *Environmental Research*, 171, 153–160. <https://doi.org/10.1016/j.envres.2019.01.020>
- Zhang, L., Petersen, E. J., & Huang, Q. (2011). Phase distribution of ¹⁴C-Labeled multiwalled carbon nanotubes in aqueous systems containing model solids: Peat. *Environmental Science & Technology*, 45(4), 1356–1362. <https://doi.org/10.1021/es1026097>
- Zhang, M., Gao, B., Chen, J., Li, Y., Creamer, A. E., & Chen, H. (2014). Slow-release fertilizer encapsulated by graphene oxide films. *Chemical Engineering Journal*, 255, 107–113. <https://doi.org/10.1016/j.cej.2014.06.023>

Chapter 7

Nanomaterials: A Promising Strategy for the Management of Microbial Plant Diseases



A. Vijaya Bhaskar Reddy, V. Madhavi, Huma Warsi Khan,
Mansoor Ul-Hassan Shah, and L. Venkatramana

Abstract Nanomaterials have emerged as promising alternatives to conventional materials to enhance the crop protection and sustainability through novel approaches. The unique physicochemical properties of nanoparticles provided applications for targeted delivery and reduced environmental pollution. This chapter explores the application of various nanomaterials including metal-based nanoparticles, carbon-based nanomaterials and polymeric nanoparticles in managing plant diseases. These nanoparticles have proved their ability to deliver agrochemicals to improve plant defence mechanism. Additionally, the ability of nanomaterials in enhancing plant immunity and growth is discussed. Further, the challenges related to toxicity, environmental impact and regulatory considerations of nanoparticles have been discussed extensively. This chapter also concluded further research to optimize nanomaterial-based strategies and to establish guidelines for their responsible use in agriculture.

Keywords Crop protection · Agrochemicals · Polymeric nanoparticles · Plant immunity · Sustainability · Biodegradability

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7.1 Introduction: Overview of Plant Diseases and Their Impact on Agriculture

Plant diseases arise due to different pathogens such as bacteria, fungi and viruses. These plant diseases pose a significant threat to global agriculture affecting crop yields, economic stability, and food security. Fungi, being the most common plant pathogens cause diseases such as rusts, smuts, mildews and blights. These diseases lead to wilting, necrosis, and reduced photosynthesis, which severely affects the crop yield (Bhatt et al., 2024). Next, the impact of bacteria on plants is severe and it causes the diseases like bacterial wilt, blight, and spot. Bacterial infections spread more rapidly under favourable conditions and hence it is difficult to control their growth (Majeed et al., 2024). On the other hand, viruses cause various plant diseases like mosaic, leaf curl, and yellowing, which leads to stunted growth, reduced vigor, and deformed plant structures. Nematodes are microscopic worms that attack the plant roots causing galls, lesions and root knots, which leads to poor nutrient uptake, reduced growth, and lower yields (Vemula & Reddy, 2023).

All the plant diseases significantly reduce the crop yields and may sometimes leads to complete crop failure. The reduced crop protection due to plant diseases impacts the global food security, especially in regions heavily dependent on agriculture for sustenance. Even in other regions of globe, it affects the food supply and can lead to higher food prices. Therefore, economic impact of plant diseases is profound, with billions of dollars lost annually due to reduced crop production, increased control costs, and loss of marketable produce (Reddy et al., 2020). Conversely, the overuse of chemical pesticides to control the plant diseases induce negative environmental consequences including soil degradation and water contamination. In most of the developing countries agriculture is a primary source of income, hence crop diseases would lead to poverty, malnutrition, and migration due to the loss of livelihoods. A summary of plant diseases and their characteristic effects are presented in Fig. 7.1 (Devi et al., 2021). Considering the adverse effects of plant diseases, effective management strategies and control methods are very much necessary to promote the sustainable agricultural practices that are crucial in mitigating the impact of these diseases (Islam et al., 2022). In recent years, wide variety of nanoparticles (NPs) have been implemented in agriculture to improve the seed germination, plant growth and development by controlling the abiotic stress in plants (Reddy et al., 2016; Aqeel et al., 2021). NPs passes through the physiological barriers and reaches the plants through roots and surface tissues. They ultimately improve the crop yield by stimulating the resistance of plants to withstand the abiotic stress (Reddy et al., 2015).

7.2 Progression of Plant Disease Control Methods

The plant disease control methods have greatly evolved over the years from conventional practices to advanced nanotechnology featuring a significant shift toward more precise, efficient and environmentally friendly approaches. The traditional

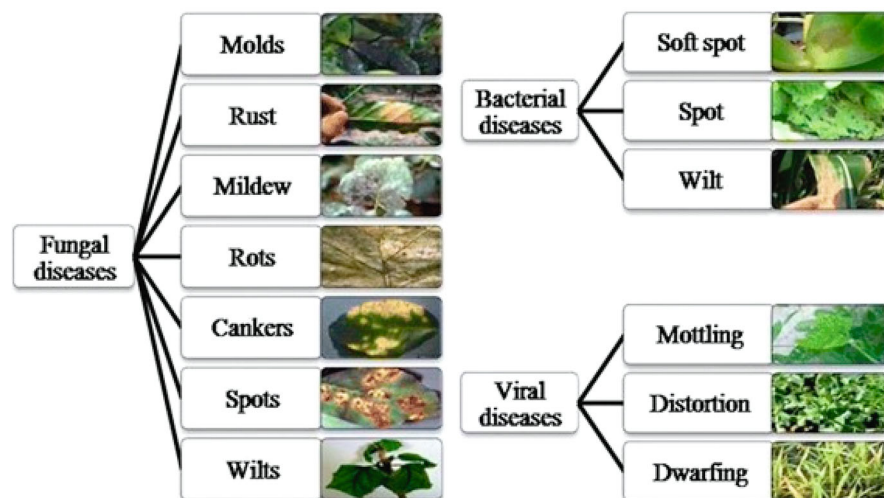


Fig. 7.1 Various types of plant diseases and their characteristic symptoms. (Reprinted from Devi et al. (2021). ©2021 The Authors. Licensed under CC BY 4.0)

methods like cultural practices, chemical treatments and biological control remain fundamental, whereas the integration of genetic engineering, molecular methods and nanotechnology have offered new possibilities for plant disease control and sustainable agriculture (Madhavi et al., 2013). These advanced methods have proved efficient to revolutionize plant disease management without affecting the environment. Various cultural practises including crop rotation and sanitation have been adopted for the decades to combat the specific plant diseases. On the other hand, chemical methods were employed to mitigate the bacterial and fungal infections with the aid of fungicides, bactericides and herbicides. However, these approaches have been proved environmentally unsafe and are dangerous to people and other species. Further, leaching of these chemicals into waterbodies pose a hazardous risk to all the living beings (Taloor et al., 2024). Considering the adverse effects of pesticides and herbicides, most of them have been banned in recent years across the globe.

Besides, the biological methods have several advantages in controlling the disease-causing bacteria, fungi and viruses over the chemical approaches. For instance, *Trichoderma* fungi parasitize harmful fungi, and *Bacillus* bacteria produce antibiotics that kill pathogens. Similarly, the molecular and genetic engineering methods helped the plants to become more resistant to specific pathogens. For example, a gene from the bacterium '*Bacillus Thuringiensis*' provides resistance to certain insect pests in genetically engineered crops. On other hand, gene editing techniques like CRISPR-CAS 9 allow for precise editing of plant genomes to enhance disease resistance by knocking out susceptibility genes or introducing resistance genes. The use of molecular markers linked to disease resistance traits to accelerate the breeding of resistant crop varieties (Kim et al., 2023).

In recent times, nanotechnology-based approaches had become promising methods for the plant disease control and crop growth. Firstly, nano-encapsulated pesticides control the release of active ingredients and reduces their environmental impact. Hence, the process improves the efficacy of chemical treatments while minimizing non-target effects. Nanoparticles of metals like silver, copper, and zinc oxide have antimicrobial properties and have been reported to control the fungal and bacterial plant pathogens. Next, nanotechnology was reported to deliver the nutrients more effectively, which enhanced plant health and makes them less susceptible to diseases. Interestingly, nano sensors can detect plant pathogens at an early stage by identifying specific volatile organic compounds (VOCs) released by infected plants and helps for timely intervention to mitigate the issue. More recently, nanoparticles have found application in delivering RNA molecules to plants that silence specific genes in pathogens, rendering them non-virulent or unable to infect plants (Zarrabian & Sherif, 2024). Various plant disease control methods are presented in Fig. 7.2 (Rajani et al., 2022).

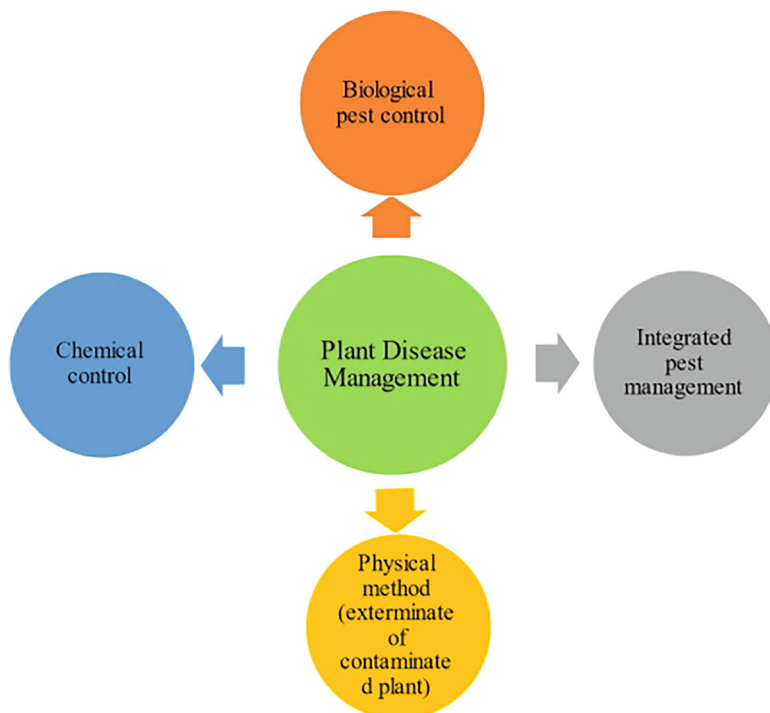


Fig. 7.2 Schematic presentation of various plant disease control methods. (Reprinted with permission from Rajani et al. (2022). ©2022 Elsevier)

7.3 Nanobiotechnology for Plant Disease Control

Nanobiotechnology combines the principles of nanotechnology and biology to create new tools, materials and technologies at the nanoscale. Its scope is being extended from medical and environmental applications to agricultural science, making it a critical field of study to address the most pressing challenges in health, food security and sustainability. At the nanoscale, biological and chemical processes can be precisely controlled by enabling advancements across the fields such as medicine, agriculture, environmental and materials science (Rasool et al., 2024). Nanobiotechnology enables the design of nanoparticles that can deliver drugs directly to targeted cells or tissues, improving the efficacy with negligible side effects. Examples include liposomes, dendrimers, and polymeric nanoparticles. Nanoscale materials, such as quantum dots and nanoparticles have been used for advanced imaging techniques and early disease diagnosis by enhancing the contrast in imaging modalities like MRI or providing highly sensitive detection of biomarkers. Additionally, nanobiotechnology is used in developing regenerative medicine and in novel therapies such as gene therapy, RNA interference (RNAi), and immunotherapy.

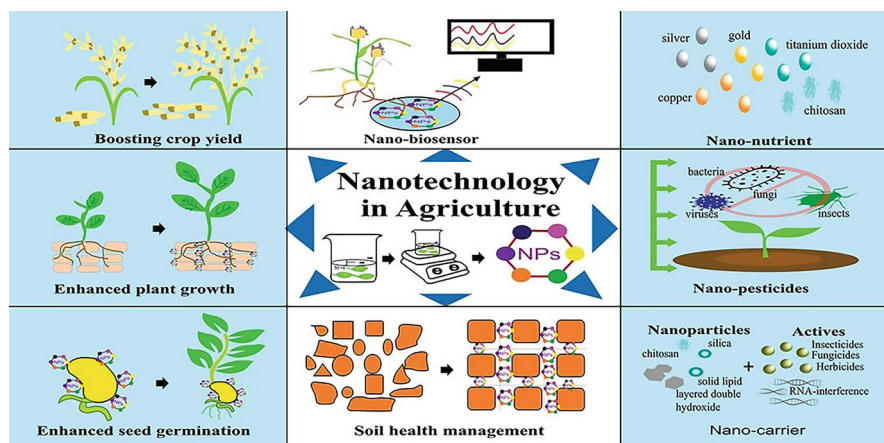
Most importantly, nanotechnology was found useful in agricultural applications for the controlled release of pesticides, fertilizers and agrochemicals through nano-encapsulation (Batool et al., 2024). For instance, starch-based nanoparticles were greatly studied for their application in safe delivery of agrochemicals and fertilizers (Machado et al., 2022). The major advantages of nano fertilizers over conventional chemical fertilizers with respect to various parameters are depicted in Table 7.1. Additionally, researchers have developed various nanoparticle based biochemical sensors and used in sustainable agriculture. These nanobiosensors have played an important role in agriculture for the effective monitoring of parameters that are relevant to plant health and environmental conditions (Shawon et al., 2020). A few nanosensors have been successfully used in agriculture to examine soil and water analysis, pesticides and nutrients supply to the plants. Further, nanotechnology enables the crop growth and resistance to diseases through the development of nanobiosensors to monitor plant health and nutrient uptake. Also, nanotechnology has been researched in plant breeding and genetic transformation (Yan et al., 2021). Numerous advantages of nanotechnology for plant growth and plant disease control are presented in Fig. 7.3 (Sarkar et al., 2022). Inspire of the benefits of nanotechnology, the agricultural sector is not using it to the greater extent. The major obstacles for its limited use are the issues related to its cost reduction, scalability and unexplained risk assessment (Ray et al., 2009).

7.4 Metal Nanoparticles for Plant Disease Control

Metal nanoparticles (MNPs) have emerged as choice of materials in agriculture for enhanced sustainability and crop productivity by controlling plant diseases. Numerous metals, metal oxides, and metalloid nanoparticles have showed strong

Table 7.1 A comparison of conventional chemical fertilizers with the nano fertilizers on various parameters

S. no	Properties	Nano fertilizers	Conventional fertilizers
1	Nutrient release and efficiency	Controlled release of nutrients over the time avoids nutrient losses.	Release nutrients rapidly, hence 40–70% of the nutrients are lost to leaching, runoff, or volatilization.
2	Absorption and uptake	NPs penetrate plant roots and tissues more effectively, leading to better utilization of micronutrients.	Nutrients are absorbed by the plant in larger particles; hence they may not be easily taken up.
3	Environmental impact	Lower environmental impact due to reduced leaching and volatilization.	High greenhouse gas emissions from nitrogen-based fertilizers.
4	Cost and application	High initial cost but reduced application frequency due to controlled release improves long-term cost efficiency.	Generally, less expensive but may require frequent applications due to nutrient loss and inefficient uptake.
5	Impact on soil health	Improved nutrient retention may benefit soil microorganisms and structure.	Excessive use can degrade soil health, reduce microbial activity, and alter soil pH over time.
6	Crop yield and quality	Improved crop yield due to enhanced nutrient delivery.	Can boost crop yield, but the results may not be consistent especially when nutrients are rapidly depleted.
7	Sustainability	More sustainable in terms of resource use as they minimize wastage and environmental degradation.	Depends on non-renewable sources, so overuse can lead to degradation of ecosystems.

**Fig. 7.3** Numerous advantages of nanotechnology in agriculture for plant development. (Reprinted with permission from Sarkar et al. (2022). ©2022 Elsevier)

bactericidal/fungicidal activity and used in agricultural applications. Due to their remarkable abilities to stimulate plant defence responses, MNPs have become essential materials for the detection of phytopathogens (Raza et al., 2024). It has been observed that, silver (Ag) ions are critical in plant growth. The reduced ethylene production by supplying Ag ions protect the plants from the risk of chlorosis and chlorophyll degradation. Further, Ag ions control the aging process of plants, promotes the synthesis of bioactive compounds and results the crop growth and production. Recently, silver nanoparticles (Ag NPs) are widely recognized for their strong antimicrobial properties towards different plant pathogens including fungi, viruses and bacteria. They disrupt the cell membranes of pathogens and make them inactive. Hence, they have been applied in foliar sprays, soil treatments and in coatings for seeds to prevent and control diseases such as bacterial blight, powdery mildew, and viral infections in crops (Adrees et al., 2019).

Similarly, copper (Cu) is critical in plant development and it serves for both structural and practical purpose. In recent times, copper nanoparticles (Cu NPs) have emerged as best alternatives for traditional copper-based fungicides and bactericides due to their penetration and effectiveness. Several Cu NPs have been used in sprays to control the fungal diseases like late blight in potatoes and bacterial diseases in various crops (Thakur et al., 2024; Ebrahimi et al., 2022). Further, iron is an important micronutrient needed for the plant growth on which the respiration and photosynthesis process depends. Iron fertilizers reduce the negative impacts and promotes the plant growth (Pourjamshid, 2021). Similarly, iron oxide nanoparticles (Fe_3O_4 NPs) were found to improve the nutrient availability in soil and hence they have been used as carriers for the controlled release of pesticides and fertilizers (E. Zhang & Liu, 2024). Several studies have reported the application of Fe NPs in the modern agriculture for the increased crop yield (Gamito et al., 2024; Singh et al., 2024; Ghafghazi et al., 2023).

Next, zinc oxide nanoparticles (ZnO NPs) provide dual benefits to the plants by supplying essential zinc nutrients and acting as antimicrobial agents against the pathogens. Recently, ZnO NPs have been used in seed coatings and foliar sprays to assist plant growth and to protect plants against diseases like downy mildew and rusts (Singh et al., 2023). Surface altered ZnO NPs are stable in colloidal suspension and aids in plant growth. Moreover, ZnO NPs enhance plant seed germination and growth, antioxidant activity, chlorophyll content and crop yield. A recent study reported that tomato crop protection against *Lactobacillus casei*, *Bacillus subtilis* and *Bacillus pumilus* was enhanced with the application of ZnO NPs. The study concluded that ZnO NPs mitigated the impacts of bacteria on tomato crop (Hosseinpour et al., 2022). On other hand, TiO_2 NPs possess photocatalytic properties that help to degrade the pathogens on plant surfaces by producing reactive oxygen species (ROS) up on exposed to light (Korosi et al., 2020). TiO_2 NPs are essentially useful in agriculture due to their improved stability and reduced toxicity. TiO_2 NPs were used to improve the seed germination, to combat the crop diseases and to break down the pesticides. They were also found useful to increase the uptake of nutrients from soil and to enhance the production of chlorophyll and carotenoids (Mustafa et al., 2020). TiO_2 NPs were found to reduce excessive Cd levels in maize.

According to a study, the maximum plant growth was obtained when TiO_2 NPs were added at 2 mg/L in turnip crop (*Brassica rapa*) (Elsaggan & Shokry, 2019).

Additionally, Si based NPs (Si NPs) have gained more attention due to their unique properties and widespread applications. Specifically, functionalized Si NPs are useful in nutrient delivery, biosensing applications and controlled release of nano-fertilizers (Rajput et al., 2021). Silicon nanotubes (Si NTs) have been used in pesticide delivery and agriculture applications owing to their biocompatibility and large inner surface area (Sharma et al., 2021). Next, mesoporous Si NPs were also well studied in agricultural applications considering their biocompatibility, high surface area and chemical stability (Boora et al., 2023). Similarly, studies have shown that SiO_2 NPs are capable to control the stress in wheat (*Triticum aestivum* L.) brought by UV-B radiation. In a study, authors reported that silica NPs have enhanced the corn (*Zea mays* L.) growth by encouraging the total biomass of the soil microbial communities (Alharbi et al., 2022). Recent studies have described that SiO_2 NPs may interact with flora and increase the plant growth by changing their shape and physiology (Goswami et al., 2022). Apart from traditional metal NPs, rare-earth elements-based NPs (REE NPs) derived from cerium, gadolinium, holmium, lanthanum, neodymium, neodymium, thulium, yttrium and ytterbium have received attention for agricultural practices due to their magnetic, catalytic and optical properties (Ferdiana et al., 2023). REE NPs proved to assist plant growth by enhancing the nutrients uptake and generating secondary metabolites. They are non-toxic and useful for sensing applications for the detection of organic pollutants (Ahmad et al., 2018). The potential benefits of REE NPs on plant is illustrated in Fig. 7.4 (Thiruvengadam et al., 2024).

The multiple benefits of MNPs help the plants against a wide range diseases and provides better resistance over traditional chemical pesticides. The greater reactivity and efficiency of MNPs reduces the environmental footprint compared to conventional agrochemicals. All these benefits of MNPs directly and indirectly help the plants providing essential nutrients that enhances plant growth, increased yield, and improved crop quality (Table 7.2).

7.5 Carbon-Based Nanomaterials for Plant Disease Control

Carbon-based nanomaterials (CBNMs) possess characteristic physicochemical properties such as high surface area, good electrical conductivity and biocompatibility. As a result, CBNMs have received significant attention for plant disease control. CBNMs physically interact with microbial cell membranes and leads to cell death. These materials can be engineered to deliver the pesticides and other agrochemicals effectively at the site of infection, minimizing waste and environmental contamination. Different carbon nanotubes (SWCNTs & MWCNTs), graphene derivatives (graphene oxide, reduced graphene oxide), carbon dots and fullerenes were useful to enhance the crop productivity by addressing plant diseases (Wu et al., 2023). Particularly, CNTs possess exceptional thermal, mechanical and

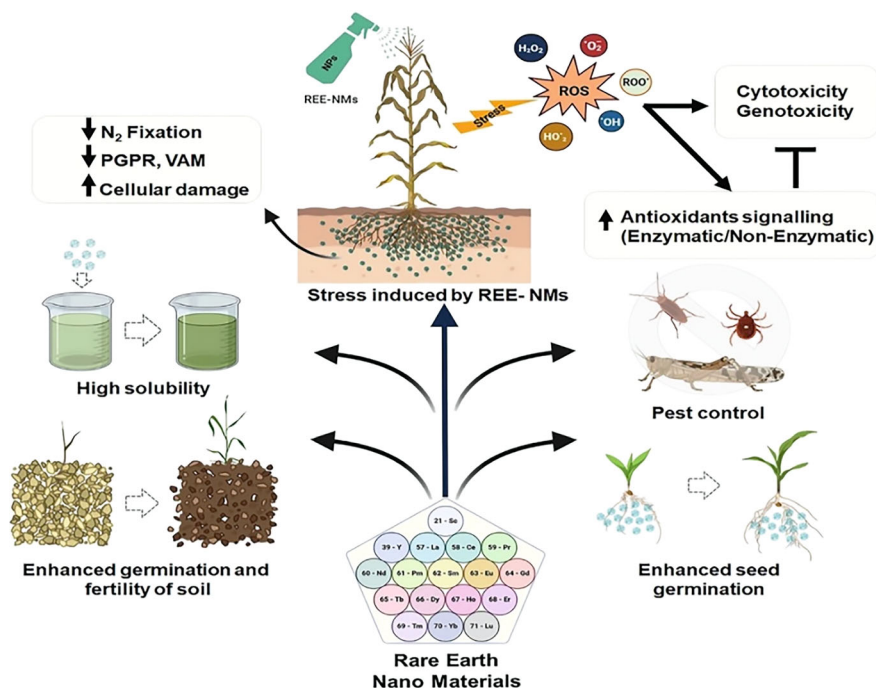


Fig. 7.4 The potential benefits of REENPs for plant management. (Reprinted with permission from Thiruvengadam et al. (2024). ©2024 Elsevier)

electrical properties. Several studies reported the use of CNTs as carriers for pesticides, enabling controlled release to infected tissues of the plant. Some functionalized CNTs have been used in biosensors for the identification of plant pathogens. They have appeared as supporting materials for the overall plant growth including seed germination and disease control making plants more resilient to diseases (Sigala-Aguilar et al., 2024).

Similarly, graphene and graphene oxide exhibit high strength, flexibility, and electrical conductivity. These materials restrict the growth of plant pathogens, including bacteria and fungi by damaging cell membranes and inducing oxidative stress. Specifically, GO-based sensors can identify specific pathogens or stress markers in plants and provide real-time monitoring in agriculture practices (Liu et al., 2024). Further, carbon dots (CDs) possess excellent biocompatibility, fluorescence and water solubility. These are easy to functionalize and can be used to develop fluorescent biosensors for the identification of plant pathogens at early stages, so that it helps to prevent the growth of pathogens on plant surfaces (Rajamanikandan et al., 2024). Fullerenes also exhibit unique electronic, photochemical, and antioxidant properties. They produce reactive oxygen species (ROS) under the light, which further kills the pathogens by damaging their critical components like DNA, proteins and lipids. Fullerenes can serve as carriers for delivering

Table 7.2 Summary of metal nanoparticles and their potential benefits in various plants

S. no	Material	Plant	Remarks
1	Ag nanoparticles	Tomato and cotton	Inhibits the growth of <i>Fusarium oxysporum</i> , the fungal pathogen causing wilt disease. Reduces the severity of <i>Alternaria alternata</i> infections.
2	Cu nanoparticles	Tomato, potato and onion	Controls <i>Phytophthora infestans</i> , the oomycete responsible for late blight in potatoes. Inhibits <i>Peronospora destructor</i> in onions by disrupting fungal growth and reproduction. Bactericidal activity against <i>Xanthomonas campestris</i> .
3	ZnO nanoparticles	Beans and cucurbits	Reduces the severity of <i>Colletotrichum lindemuthianum</i> infections in beans. Controls <i>Erysiphe cichoracearum</i> , the fungal pathogen causing powdery mildew in cucurbits.
4	TiO ₂ nanoparticles	Roses and tomatoes	Inhibit the growth of <i>Sphaerotheca pannosa</i> , responsible for powdery mildew in roses. Reduces the severity of <i>Fusarium oxysporum</i> infections in tomato plants and improve defence mechanism.
5	MgO nanoparticles	Wheat	Effective in reducing infections caused by <i>Fusarium spp.</i> in wheat.
6	Si nanoparticles	Wheat and rice	Si NPs effectively controls <i>Blumeria graminis</i> , the fungal pathogen responsible for powdery mildew. Reduce the severity of <i>Magnaporthe oryzae</i> infections in rice.

fungicides and bactericides to infected plants so that it enhances the efficacy and reduces the environmental impact occurs through organic pesticides (Bityutskii et al., 2023). Several scientific studies have documented the benefit of C₆₀ in plant disease control (Holghoomi & Colagar, 2024). In a recent study, authors described the foliar applications of C₆₀ towards improving *chlorophyll b* and carotenoids in Jelitto and Pharmasaat varieties of chamomile (*Tanacetum parthenium* L.) (Ahmadi et al., 2020). Another study reported the increased content of biocompounds such as lycopene, insulin, charantine and cucurbitacin-B in melon fruits (*Momordica charantia* L.) when treated the seeds with 10.8 mM of C₆₀(OH)₂₀. At the same time, when the seeds were treated with 40 nM of C₆₀(OH)₂₀, the concentrations of phenols, ascorbic acid and amino acids were increased in wheat (*Triticum aestivum* L.). Further, when treated with 80 nM of C₆₀(OH)₂₀ the concentrations of phenols, flavonoids and amino acids were impacted the ascorbate peroxidase (APX) (Kole et al., 2013).

Another study reported that the cucumber plants (*Cucumis sativus* L.) were grown hydroponically when supplied with 750 mg/L of C₆₀(OH)_{22–24} nutrient solution. They claimed that C₆₀ addition increased the levels of fatty acid esters and carboxylic acids in plants. Further, the contents of lycopene in tomato fruits (*Solanum lycopersicum* L.), and chlorophylls in seedling cherry tomatoes were increased with the application of 200 mg/L of C₆₀(OH)_{24–45} (Bityutskii et al., 2020). A study reported that graphene usage in foliar applications of pepper (*Cap-sicum annuum* L.) and eggplant (*Solanum melongena* L.) plants resulted higher

yields. It has also enhanced the activity of phenylalanine ammonium lyase (PAL) and glutathione transferase (GST) (Younes et al., 2019). Other study reported that the usage silver-graphene in foliar application of mint (*Melissa officinalis* L.) favoured the gene expression of tyrosine aminotransferase enzyme and rosmarinic acid synthase (RAS) (Soraki et al., 2021). Similarly, another study reported the in-vitro treatment of thyme (*Thymus daenensis* L.) with SWCNTs at 50 mg/L in seedlings enhanced the levels of phenols, catechin, flavonoids, cymophenol and rosmarinic acid (Samadi et al., 2020). The other study claimed hydroponic growth in maize plants assisting photosynthesis, respiration, intercellular carbon dioxide (CO₂) and soluble proteins. The same study reported the improvement of glutamine synthase, nitrate reductase, glutamate synthase, sucrose phosphate synthase and phosphoenolpyruvate carboxylase activity (Hu et al., 2021).

The efficiency of CBNMs in delivering agrochemicals and their direct antimicrobial properties reduces the need for large quantities of chemical pesticides, leading to a decrease in environmental pollution. They are more environmentally friendly compared to traditional chemical treatments, as they can be designed to degrade into non-toxic by-products and reduce the chemical load in the environment. Apart from the above, the use of CBNMs allows for more precise application of treatments, reducing the impact on non-target organisms and ecosystems and enhances the sustainability of agricultural practices (Table 7.3).

Table 7.3 Summary of different carbon-based nanomaterials and their advantages for plant growth and disease control

S. no	Material	Plant	Remarks
1	Carbon nanotubes	Tobacco, tomato and rice	Deliver antiviral agents to tobacco plants and reduces the spread of TMV infections by acting as a carrier. Improves plant plant's immune system against <i>Fusarium oxysporum</i> . Reduce <i>Xanthomonas oryzae</i> populations through disruption of bacterial cell walls.
2	Graphene oxide	Strawberries and tomatoes	Inhibit the growth of <i>Botrytis cinerea</i> , a fungal pathogen causing grey mold in strawberries. Shows antibacterial activity against <i>Xanthomonas campestris</i> that improving plant health.
3	Fullerenes	Wheat, tomato and tobacco	Reduces <i>Blumeria graminis</i> infections by generating ROS under sunlight. Exhibit antiviral properties against TMV in tobacco plants. Shows effectiveness in reducing <i>Fusarium oxysporum</i> infections.
4	Carbon dots	Beans, pepper and cucumber	Controls <i>Colletotrichum lindemuthianum</i> , the fungal pathogen in beans. Exhibit antibacterial activity against <i>Xanthomonas campestris</i> in pepper plants.
5	Activated carbon	Beans and tomato	Adsorbs pathogenic spores of <i>Rhizoctonia solani</i> , reduces root rot severity and improves plant growth. Adsorbs and neutralize <i>Ralstonia solanacearum</i> populations in the soil, to eradicate bacterial wilt.

7.6 Nanopolymers and Nanocomposites for Plant Disease Control

Nanopolymers and nanocomposites have emerged as innovative tools offering new strategies for plant disease control. These materials combine the unique properties of nanoscale substances with polymers to create advanced materials that can effectively prevent, manage, and treat plant diseases. Their applications range from enhancing the delivery of agrochemicals to promoting more sustainable and efficient agricultural practices. These materials comprise specific properties such as increased reactivity, smart drug delivery and sustained release of active ingredients. Therefore, they have been used in making of encapsulated agrochemicals allowing their controlled and sustained release. This confirms that the active ingredients are delivered over an extended period reducing the need of frequent application (Parkinson et al., 2022). Further, encapsulation of pesticides within nanopolymers enhances their stability and effectiveness prevailing their action against pathogens while reducing off-target effects and environmental contamination. Additionally, nanopolymers can be tuned to discharge the agrochemicals to the site of infection, which minimizes the amount of chemical needed. Some nanopolymers used to deliver essential nutrients to plants that promotes the growth while enhancing the plants resistance to diseases. The slow release of nutrients ensures continuous availability to the plants, improving overall health and reducing vulnerability to pathogens. Nanopolymer-based coatings have been applied for seed coatings to protect them from pathogens in the soil and enhance germination and early growth. In some studies, nanopolymers have been combined with other antimicrobial agents such as silver nanoparticles to improve their efficacy against diverse plant pathogens (Hashim et al., 2020; Darwish et al., 2022).

Nanocomposites are polymers reinforced with nanoparticles (up to 5% by weight) to enhance the polymers performance (Yadav et al., 2023). A study observed that nano zinc oxide and nano magnesium oxide polymer nanocomposites exhibit diverse chemical activity and are used in food packaging applications to restrict the oxygen, CO₂ and moisture (Chhikara et al., 2014). A study reported the synthesis of polyhydroxyalkanoate (PHA) and calcium phosphate nanoparticles (Ca-P-NPs) and tested its effectiveness as a P-delivery vehicle in tomato. The efficacy of the nanocomposite was assessed with respect to plant biomass, crop yield and chlorophyll content. The study disclosed that PHA-Ca-P PNCs improved the plant performance over the conventional P source, while decreasing P loss from the soil by more than 80% (Sigmon et al., 2021) (Table 7.4).

Table 7.4 A summary of different nanopolymer composites and their benefits on plants growth

S. no	Material	Plant	Remarks
1	Chitosan nanoparticles	Tomato and cucumber	Effectively reduces <i>Fusarium oxysporum</i> infections in tomato plants and directly inhibiting fungal growth. Reduces the severity of <i>Erysiphe cichoracearum</i> infections in cucumber by strengthening plant cell walls.
2	Alginate nanoparticles	Tomato and rice	Control <i>Ralstonia solanacearum</i> , reducing bacterial populations and disease severity in tomato plants. Controls <i>Rhizoctonia solani</i> infections reducing pathogen survival.
3	PEG nanoparticles	Tomato and cucurbits	Reduces the infection caused by <i>Podosphaera xanthii</i> and delivers the leaf surfaces of cucurbits. Controls <i>Xanthomonas campestris</i> infections by enhancing copper ion delivery to the bacterial cells.
4	Lignin nanoparticles	Strawberries	Control <i>Botrytis cinerea</i> , the fungus causing grey mold, by providing a sustained release of the active ingredient, reducing fungal growth.

7.7 Organic Nanomaterials for Plant Disease Control

Organic nanomaterials represent a class of nanoparticles (NPs) composed of organic substances such as natural compounds, biopolymers and other carbon-based materials. Their biocompatibility, biodegradability and potential for targeted action make them attractive alternatives to conventional inorganic nanomaterials. Nanoparticles derived through biopolymers such as polysaccharides (e.g., chitosan, alginate), proteins (e.g., casein, gelatin), and nucleic acids (e.g., DNA) **have been widely** used for the encapsulation of agrochemicals that enhances the nutrient delivery and antimicrobial action (Patel, 2021). Several natural nanoparticles derived from biological sources and plant extracts have found significant application in sustainable agriculture along with their biodegradable and environmentally friendly nature. Hybrid nanomaterials such as metal-organic frameworks (MOFs) provide synergistic effects like enhanced stability and controlled release for plant disease management. Several studies reported that organic nanomaterials display strong antimicrobial properties against plant pathogens. For instance, chitosan-based NPs have shown effectiveness in controlling fungal diseases like powdery mildew and rust (Meena et al., 2023). When combined with other antimicrobial agents, organic nanomaterials can encapsulate the pesticides and agrochemicals that helps in controlled and sustained release. Like metal-based nanomaterials, organic nanomaterials have found their application in biosensors for the identification of plant pathogens. Besides, the organic nanomaterials improved the plant tolerance to abiotic stress like drought and salinity by enhancing nutrient uptake and protecting plants from oxidative damage. This indirect disease control helps plants remain healthy and less susceptible to pathogens (Vinzant et al., 2023).

Biostimulants such as humic acids, fulvic acids, seaweed extracts, amino acids, alginate and microalgae promotes the plant growth by inducing root and shoot

growth, plant nutrient uptake and biogenic synthesis of plant growth regulators. Therefore, biostimulants are natural and environmentally safe substitutes to synthesise plant growth regulators and agrochemicals such as pesticides for sustainable crop productivity. Also, biobased NMs derived from chitosan, chitin, cellulose, and silica have been appeared as promising materials to strengthen the plants against various modes of stress owing to their superior characteristics (Popa et al., 2022).

Cellulose, a linear polymer of glucose connected by β -1,4-glycosidic bonds, serves as a precursor for the development of nanocellulose particles. Nanocellulose is often synthesized using plant-based materials. Chitosan is the N-deacetylated product of chitin that has been used in many industrial applications (Bagal-Kestwal et al., 2016). In addition, lignin-based NPs have offered excellent antioxidant and antimicrobial properties to plants. Hence, they have been widely studied for the development of nanocarriers (Pereira et al., 2022). A summary of nanomaterials employed in plant growth and plant management are depicted below in Fig. 7.5 (Zhang et al., 2024).

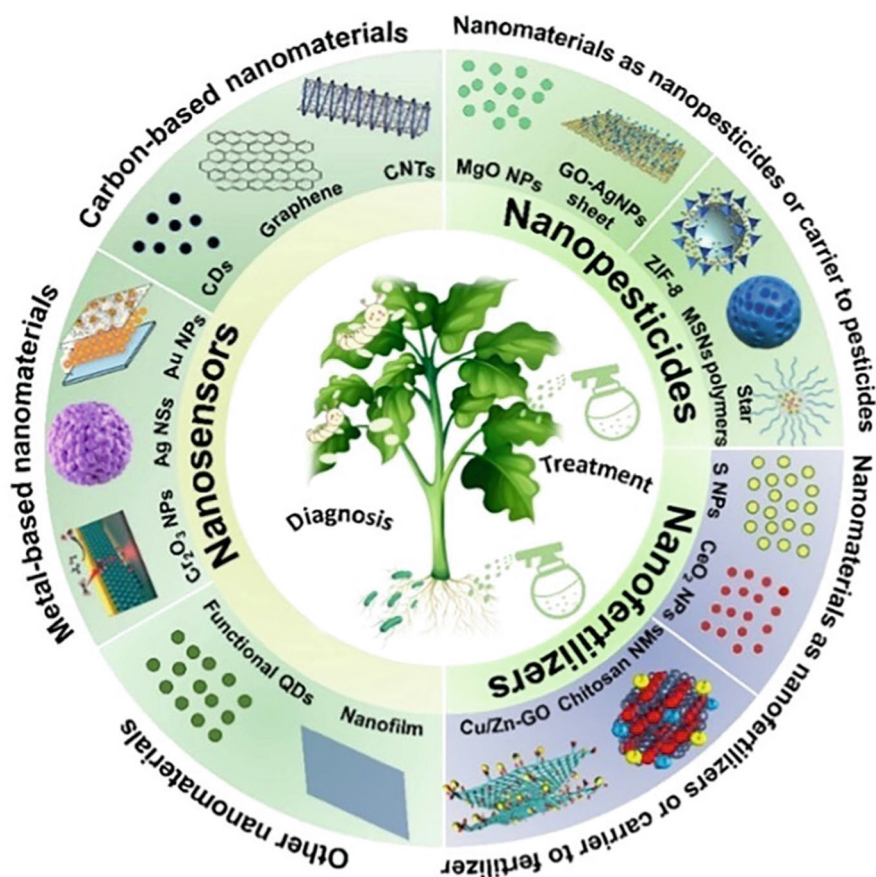


Fig. 7.5 Different nanomaterials employed in plant disease diagnosis and treatment. (Reprinted with permission from Zhang et al. (2024). ©2024 Elsevier)

7.8 Economic Considerations and Cost-Benefit Analysis

The application of nanotechnology in agriculture has provided opportunities for improved crop productivity, disease control and sustainable farming practices. However, the economic feasibility of implementing nanotechnology in agriculture must be carefully evaluated through a cost-benefit analysis (CBA). This analysis must examine the financial costs, potential economic benefits, and broader economic implications of NPs in agriculture to help the stakeholders. The CBA evaluates the economic viability of different nanoparticles use in agriculture by comparing the costs incurred with the expected benefits providing the comprehensive understanding of economic impact (Brent, 2023).

The production cost of NPs varies significantly with the type, size, and surface functionalization. High-quality NPs often require complex and expensive synthesis processes, advanced materials, specialized equipment and skilled labour. Next, the large-scale production of NPs involves the additional costs related to equipment, energy, raw materials. On other hand, the availability and cost of raw materials used in NP synthesis such as metals (e.g., silver, gold), metal oxides (e.g., zinc oxide, titanium dioxide), or carbon-based materials (e.g., graphene), significantly impacts the overall production cost. After the synthesis of NPs, effective formulations and drug delivery systems such as encapsulation, coatings and nanocarriers adds to the overall cost. These technologies are necessary to ensure the stability, bioavailability, and controlled release of NPs. Nevertheless, utilisation of NP-based solutions requires specialized agricultural equipment such as precision sprayers and sensors for their effective use. The cost of upgrading or purchasing new equipment can be a significant consideration for farmers. Further, the farmers from developing regions might be sensitive to high cost associated with NP-based products. The economic benefits of these products must be clearly demonstrated to justify their higher costs compared to conventional alternatives.

The initial costs of adopting NP-based technologies include research and development (R&D), production, regulatory approval, and equipment upgrades. These upfront investments are crucial for bringing NP products to market but can be substantial. Ongoing costs include the purchase of NP-based products, application and management expenses, labour, and compliance with regulations. These costs must be weighed against the benefits to determine long-term viability. The use of NPs in agriculture likely improves the quality of agricultural products by enhancing plant health and reducing disease incidence. Higher quality produce often commands better market prices, contributing to increased income for farmers, which needs a detailed study for different crops. Apart from the above, the adoption of NP-based technologies introduces market risks, such as fluctuating prices of raw materials, changes in consumer preferences, and the emergence of competing technologies. These risks can affect the profitability of NP-based agriculture. Other than the above discussed, the adoption of nanotechnology in agriculture can stimulate economic

development, particularly in rural areas, by creating new markets, jobs, and opportunities for innovation in the agricultural sector. While NPs offer significant potential for enhancing crop productivity, reducing agrochemical use, and promoting sustainability, their adoption involves substantial initial investments, operational costs, and potential environmental and health risks. Stakeholders including farmers, agribusinesses, policymakers, and researchers must carefully evaluate the financial and broader economic implications of NPs to ensure that their adoption leads to sustainable and profitable agricultural practices.

7.9 Environmental Impact of Nanoparticles in Agriculture

The unique advantages of NPs usage in agriculture have provided effective and environmentally friendly solutions for managing pathogens, improving crop yields, and promoting soil health. However, the challenges related to toxicity, regulation and cost must be addressed to fully realize their potential in agriculture. Continued research, technological innovation, and regulatory oversight will play key roles in maximizing the benefits of NPs while minimizing their economic and environmental risks.

- Increasing consumer demand for organic and eco-friendly products may influence the adoption of NP-based technologies. If consumers perceive NPs as potentially harmful or non-organic, this could limit market demand. Therefore, it is very important to conduct enhanced toxicity assessment of NPs to ensure their non-toxicity and biodegradability.
- The cost of producing and applying MNPs can be higher than traditional agrochemicals, which may limit their adoption especially in resource-constrained settings. Hence, production MNPs at low cost and easy accessibility to farmers in various regions is critical for their widespread adoption.
- While NPs offer environmental benefits, some NPs may pose risks, including soil and water contamination, which could lead to long-term environmental remediation costs. The long-term impacts of NPs in the soil and water ecosystems require thorough study to ensure safe use.
- The potential health risks of farmers, workers, and consumers when exposed to NPs may lead to increased healthcare costs and the need for safety measures, such as protective equipment and monitoring systems. So detailed examination of NPs effect on human and other living organisms is much required field.
- While MNPs are effective against pathogens, their impact on beneficial microbes, insects, and soil fauna, needs to be carefully evaluated. Similarly, CBNMs, nanopolymers and nanocomposites offer many benefits, their potential toxicity to plants, non-target organisms, and humans must be carefully evaluated. Long-term studies are needed to assess their safety in agricultural environments.

7.10 Concluding Remarks and Future Perspectives

The number of research articles and patents published on the application of nanotechnology in agriculture is gradually increased, but the research is still far from being conclusive. The consumption of different nanoparticles in agriculture has opened new avenues for enhancing crop production, disease control and sustainability. While nanoparticles offer significant benefits for agriculture like disease diagnosis and control, nutrient delivery and improved crop productivity, their environmental impact is a growing concern. As their use increases, understanding the potential risks and long-term effects on ecosystems, soil health and biodiversity becomes crucial. Additionally, the cost efficiency and energy consumption are further restricting the use of nanotechnology in agriculture. At the industrial level, collaboration between researchers and industry professionals is essential for the large-scale production of nanoparticles with optimized efficiency.

NPs can interact with soil microbial communities that are critical in nutrient cycling, organic matter decomposition and plant health. But some NPs, such as Ag NPs and Cu NPs have antimicrobial properties that may disrupt beneficial microbial populations, hence the interference of NPs with soil organisms such as earthworms, nematodes, and arthropods, which are essential for maintaining soil health should be extensively studied. In water bodies, NPs can interact with aquatic organisms, potentially causing toxicity. NPs may accumulate in aquatic organisms, which leads to bioaccumulation and biomagnification in the food chain. For example, MNPs like silver and zinc oxide can induce oxidative stress in fish, algae, and other aquatic life, leading to reduced growth, reproduction, and survival rates. So a thorough understanding of NPs interaction with aquatic life is necessary to be conducted. Potential risks to soil health, water quality, air quality, and biodiversity underscore the need for responsible use, rigorous risk assessment, and ongoing research. By adopting sustainable practices, developing safer nanomaterials, and implementing effective regulatory measures, it is possible to harness the advantages of nanoparticles in agriculture while minimizing their environmental footprint. Promoting the development of environmentally friendly NPs, such as those made from biodegradable or natural materials, can reduce the environmental impact. Supporting long-term studies on the environmental fate and impact of NPs in agriculture is essential to understand their cumulative effects on ecosystems and to develop strategies for their safe use.

Overall, nanotechnology plays a crucial role in advancing agriculture by enhancing crop productivity and quality, and it has also found widespread application in various areas of the food industry. Future research efforts are aimed at fostering sustainable development in nano-enabled agriculture.

References

- Adrees, M., Khan, Z. S., Ali, S., Hafeez, M., Khalid, S., Rehman, M. Z. U., Hussain, A., Hussain, K., Chatha, S. A. S., & Rizwan, M. (2019). Simultaneous mitigation of cadmium and drought stress in wheat by soil application of iron nanoparticles. *Chemosphere*, 238, 124681. <https://doi.org/10.1016/j.chemosphere.2019.124681>
- Ahmad, H. R., Zia-Ur-Rehman, M., Sohail, M. I., ul Haq, M. A., Khalid, H., Ayub, M. A., & Ishaq, G. (2018). Effects of rare earth oxide nanoparticles on plants. In *Elsevier eBooks* (pp. 239–275). <https://doi.org/10.1016/b978-0-12-811487-2.00011-6>
- Ahmadi, S. Z., Ghorbanpour, M., Aghaee, A., & Hadian, J. (2020). Deciphering morpho-physiological and phytochemical attributes of *Tanacetum parthenium* L. plants exposed to C60 fullerene and salicylic acid. *Chemosphere*, 259, 127406. <https://doi.org/10.1016/j.chemosphere.2020.127406>
- Alharbi, K., Hafez, E., Omara, A. E., Awadalla, A., & Nehela, Y. (2022). Plant growth promoting rhizobacteria and silica nanoparticles stimulate sugar beet resilience to irrigation with saline water in salt-affected soils. *Plants*, 11(22), 3117. <https://doi.org/10.3390/plants11223117>
- Aqeel, U., Aftab, T., Khan, M. M. A., Naeem, M., & Khan, M. N. (2021). A comprehensive review of impacts of diverse nanoparticles on growth, development and physiological adjustments in plants under changing environment. *Chemosphere*, 291, 132672. <https://doi.org/10.1016/j.chemosphere.2021.132672>
- Bagal-Kestwal, D. R., Kestwal, R. M., & Chiang, B. H. (2016). Bio-based nanomaterials and their bionanocomposites. In *Nanomaterials and nanocomposites* (pp. 255–330). Wiley. <https://doi.org/10.1002/9783527683772.ch8>
- Batool, A., Nazir, M., & Zargar, S. M. (2024). Nano-pesticides and nano-fertilizers from natural (plant/animal) wastes. *Biocatalysis and Agricultural Biotechnology*, 60, 103265. <https://doi.org/10.1016/j.bcab.2024.103265>
- Bhatt, B., Gupta, S. K., Mukherjee, S., & Kumar, R. (2024). A comprehensive review on biochar against plant pathogens: Current state-of-the-art and future research perspectives. *Heliyon*, 10(17), e37204. <https://doi.org/10.1016/j.heliyon.2024.e37204>
- Bityutskii, N. P., Yakkonen, K. L., Lukina, K. A., & Semenov, K. N. (2020). Fullerenol increases effectiveness of foliar iron fertilization in iron-deficient cucumber. *PLoS One*, 15(5), e0232765. <https://doi.org/10.1371/journal.pone.0232765>
- Bityutskii, N. P., Yakkonen, K. L., Napolskikh, Y. M., Pampur, D., Yuriev, G. O., Semenov, K. N., & Letenko, D. G. (2023). Protective role of fullerenol and arginine C60 fullerene against copper toxicity in cucumber. *Plant Physiology and Biochemistry*, 204, 108095. <https://doi.org/10.1016/j.plaphy.2023.108095>
- Boora, R., Rani, N., Kumari, S., Yashveer, S., Kumari, N., & Grewal, S. (2023). Efficacious role of silica nanoparticles in improving growth and yield of wheat under drought stress through stress-gene upregulation. *Plant Nano Biology*, 6, 100051. <https://doi.org/10.1016/j.plana.2023.100051>
- Brent, R. J. (2023). Cost-benefit analysis versus cost-effectiveness analysis from a societal perspective in healthcare. *International Journal of Environmental Research and Public Health*, 20(5), 4637. <https://doi.org/10.3390/ijerph20054637>
- Chhikara, D., Srivatsa, K., & Muthusamy, S. K. (2014). On the synthesis and characterization of ZnO/MgO nanocomposite by thermal evaporation technique. *Solid State Sciences*, 37, 108–113. <https://doi.org/10.1016/j.solidstatesciences.2014.09.002>
- Darwish, M. S. A., Mostafa, M. H., & Al-Harbi, L. M. (2022). Polymeric nanocomposites for environmental and industrial applications. *International Journal of Molecular Sciences*, 23(3), 1023. <https://doi.org/10.3390/ijms23031023>
- Devi, N., Leela Rani, P., Guru Gokul, A. R., Kannadasan, R., Alsharif, M. H., Alsharif, M. H., Jahid, A., & Khan, M. A. (2021). Categorizing diseases from leaf images using a hybrid learning model. *Symmetry*, 13(11), 2073. <https://doi.org/10.3390/sym13112073>

- Ebrahimi, Z., Biabani, A., Mohammadi, R. A., Sabouri, H., & Karizaki, A. R. (2022). Response of physiological and biochemical characteristics of Aseman wheat cultivar to foliar application zinc and iron micronutrient in dryland conditions. *Journal of Crop Breeding*, 14(41), 53–62. <https://doi.org/10.52547/jcb.14.41.53>
- Elsaggan, M., & Shokry, A. (2019). Impact of bio-fertilizer and TiO₂ nanoparticles spray on growth, productivity and pickle quality of turnip crop (brassica rapa). *Egyptian Journal of Desert Research*, 69(1), 101–121. <https://doi.org/10.21608/ejdr.2019.108099>
- Ferdiana, N. A., Bahti, H. H., Kurnia, D., & Wyantuti, S. (2023). Synthesis, characterization, and electrochemical properties of rare earth element nanoparticles and its application in electrochemical nanosensor for the detection of various biomolecules and hazardous compounds: A review. *Sensing and Bio-Sensing Research*, 41, 100573. <https://doi.org/10.1016/j.sbsr.2023.100573>
- Gamito, G., Monteiro, C. J., Dias, M. C., Oliveira, H., Silva, A. M., Faustino, M. A., & Silva, S. (2024). Impact of Fe₃O₄-porphyrin hybrid nanoparticles on wheat: Physiological and metabolic advance. *Journal of Hazardous Materials*, 471, 134243. <https://doi.org/10.1016/j.jhazmat.2024.134243>
- Ghafghazi, L., Taghavi, L., Rasekh, B., Farahani, H., & Hassani, A. H. (2023). Application of compost assisted by Fe₃O₄ nanoparticles in di (2-ethylhexyl) phthalate-contaminated soil remediation: Biostimulation strategy, soil responses, and RSM/CCD optimization. *The Science of the Total Environment*, 908, 168029. <https://doi.org/10.1016/j.scitotenv.2023.168029>
- Goswami, P., Mathur, J., & Srivastava, N. (2022). Silica nanoparticles as novel sustainable approach for plant growth and crop protection. *Heliyon*, 8(7), e09908. <https://doi.org/10.1016/j.heliyon.2022.e09908>
- Hashim, A. F., Youssef, K., Roberto, S. R., & Abd-Elsalam, K. A. (2020). Hybrid inorganic-polymer nanocomposites: Synthesis, characterization, and plant-protection applications. In *Elsevier eBooks* (pp. 33–49). <https://doi.org/10.1016/b978-0-12-821354-4.00003-0>
- Holghoomi, R., & Colagar, A. H. (2024). Applications of biocompatible nanoparticles in plant biotechnology for enhanced secondary metabolite biosynthesis. *Inorganic Chemistry Communications*, 167, 112753. <https://doi.org/10.1016/j.inoche.2024.112753>
- Hosseinpour, P., Hosseinpour, M., & Sharifi, Y. (2022). Artificial neural networks for predicting ultimate strength of steel plates with a single circular opening under axial compression. *Ships and Offshore Structures*, 17(11), 2454–2469. <https://doi.org/10.1080/17445302.2021.2000265>
- Hu, Y., Zhang, P., Zhang, X., Liu, Y., Feng, S., Guo, D., Nadezhda, T., Song, Z., & Dang, X. (2021). Multi-wall carbon nanotubes promote the growth of maize (*Zea mays*) by regulating carbon and nitrogen metabolism in leaves. *Journal of Agricultural and Food Chemistry*, 69(17), 4981–4991. <https://doi.org/10.1021/acs.jafc.1c00733>
- Islam, F., Shohag, S., Uddin, M. J., Islam, M. R., Nafady, M. H., Akter, A., Mitra, S., Roy, A., Emran, T. B., & Cavalu, S. (2022). Exploring the journey of zinc oxide nanoparticles (ZnO-NPs) toward biomedical applications. *Materials*, 15(6), 2160. <https://doi.org/10.3390/ma15062160>
- Kim, K., Kim, C. K., & Kim, W. (2023). The strategy of knock-in with homology-directed genome editing in the model ornamental plant *Petunia* using CRISPR/Cas9 ribonucleoprotein complex. *Scientia Horticulturae*, 326, 112714. <https://doi.org/10.1016/j.scienta.2023.112714>
- Kole, C., Kole, P., Randunu, K. M., Choudhary, P., Podila, R., Ke, P. C., Rao, A. M., & Marcus, R. K. (2013). Nanobiotechnology can boost crop production and quality: First evidence from increased plant biomass, fruit yield and phytochemistry content in bitter melon (*Momordica charantia*). *BMC Biotechnology*, 13(1). <https://doi.org/10.1186/1472-6750-13-37>
- Korosi, L., Pertics, B., Schneider, G., Bognár, B., Kovács, J., Meynen, V., Scarpellini, A., Pasquale, L., & Prato, M. (2020). Photocatalytic inactivation of plant pathogenic bacteria using TiO₂ nanoparticles prepared hydrothermally. *Nanomaterials*, 10(9), 1730. <https://doi.org/10.3390/nano10091730>

- Liu, W., Zhang, Z., Geng, X., Tan, R., Xu, S., & Sun, L. (2024). Electrochemical sensors for plant signaling molecules. *Biosensors and Bioelectronics*, 267, 116757. <https://doi.org/10.1016/j.bios.2024.116757>
- Machado, T. O., Grabow, J., Sayer, C., De Araújo, P. H., Ehrenhard, M. L., & Wurm, F. R. (2022). Biopolymer-based nanocarriers for sustained release of agrochemicals: A review on materials and social science perspectives for a sustainable future of agri- and horticulture. *Advances in Colloid and Interface Science*, 303, 102645. <https://doi.org/10.1016/j.cis.2022.102645>
- Madhavi, V., Prasad, T., Reddy, A. V. B., Reddy, B. R., & Madhavi, G. (2013). Application of phytogetic zerovalent iron nanoparticles in the adsorption of hexavalent chromium. *Spectrochimica Acta Part a Molecular and Biomolecular Spectroscopy*, 116, 17–25. <https://doi.org/10.1016/j.saa.2013.06.045>
- Majeed, G., Noor, W., Lone, R., Agrawal, S., Alaklabi, A., Shah, M. A., & Kamili, A. N. (2024). Modulation of plant defenses by jasmonic acid and salicylic acid in *Capsicum annuum* L. against *Fusarium* wilt in response to *Fusarium oxysporum* pathogen. *Plant Stress*, 14, 100571. <https://doi.org/10.1016/j.stress.2024.100571>
- Meena, K., Meena, N., Meena, R. N., Choudhary, M., Meena, S., & Kumar, S. (2023). Role of nanotechnology in organic agriculture. In *Elsevier eBooks* (pp. 343–364). <https://doi.org/10.1016/b978-0-323-99145-2.00015-x>
- Mustafa, M. A., Mabhaudhi, T., & Massawe, F. (2020). Building a resilient and sustainable food system in a changing world—A case for climate-smart and nutrient dense crops. *Global Food Security*, 28, 100477. <https://doi.org/10.1016/j.gfs.2020.100477>
- Parkinson, S. J., Tungsirirup, S., Joshi, C., Richmond, B. L., Gifford, M. L., Sikder, A., Lynch, I., O'Reilly, R. K., & Napier, R. M. (2022). Polymer nanoparticles pass the plant interface. *Nature Communications*, 13(1). <https://doi.org/10.1038/s41467-022-35066-y>
- Patel, A. (2021). Application of nano organic materials in agriculture farming and yield analysis for groundnut crop with comparison to conventional inorganic farming. *IOP Conference Series Earth and Environmental Science*, 785(1), 012008. <https://doi.org/10.1088/1755-1315/785/1/012008>
- Pereira, A. D. E. S., De Oliveira, J. L., Savassa, S. M., Rogério, C. B., De Medeiros, G. A., & Fraceto, L. F. (2022). Lignin nanoparticles: New insights for a sustainable agriculture. *Journal of Cleaner Production*, 345, 131145. <https://doi.org/10.1016/j.jclepro.2022.131145>
- Popa, D. G., Lupu, C., Constantinescu-Aruxandei, D., & Oancea, F. (2022). Humic substances as microalgal biostimulants—Implications for microalgal biotechnology. *Marine Drugs*, 20(5), 327. <https://doi.org/10.3390/md20050327>
- Pourjamshid, S. A. (2021). Study the effect of iron, zinc and manganese foliar application on morphological and agronomic traits of bread wheat (Chamran cultivar) under different irrigation regimes. *Environmental Stresses in Crop Sciences*, 14, fa109–fa118. <https://doi.org/10.22077/escs.2020.2448.1643>
- Rajamanikandan, R., Prabakaran, D., Sasikumar, K., Seok, J. S., Lee, G., & Ju, H. (2024). Biocompatible bright orange emissive carbon dots: Multifunctional nanoprobe for highly specific sensing toxic Cr(VI) ions and mitochondrial targeting cancer cell imaging. *Talanta Open*, 10, 100353. <https://doi.org/10.1016/j.talo.2024.100353>
- Rajani, N., Mishra, P., Kumari, S., Saini, P., & Meena, R. K. (2022). Role of nanotechnology in management of plant viral diseases. *Materials Today Proceedings*, 69, 1–10. <https://doi.org/10.1016/j.matpr.2022.06.355>
- Rajput, V. D., Harish, N., Singh, R. K., Verma, K. K., Sharma, L., Quiroz-Figueroa, F. R., Meena, M., Gour, V. S., Minkina, T., Sushkova, S., & Mandzhieva, S. (2021). Recent developments in enzymatic antioxidant defence mechanism in plants with special reference to abiotic stress. *Biology*, 10(4), 267. <https://doi.org/10.3390/biology10040267>
- Rasool, A., Sri, S., Zulfajri, M., & Krismastuti, F. S. H. (2024). Nature inspired nanomaterials, advancements in green synthesis for biological sustainability. *Inorganic Chemistry Communications*, 169, 112954. <https://doi.org/10.1016/j.inoche.2024.112954>

- Ray, P. C., Yu, H., & Fu, P. P. (2009). Toxicity and environmental risks of nanomaterials: Challenges and future needs. *Journal of Environmental Science and Health Part C*, 27(1), 1–35. <https://doi.org/10.1080/10590500802708267>
- Raza, A., Khandelwal, K., Pandit, S., Singh, M., Kumar, S., Rustagi, S., Ranjan, N., Verma, R., Priya, K., & Prasad, R. (2024). Exploring the potential of metallic and metal oxide nanoparticles for reinforced disease management in agricultural systems: A comprehensive review. *Environmental Nanotechnology Monitoring & Management*, 22, 100998. <https://doi.org/10.1016/j.enmm.2024.100998>
- Reddy, A. V. B., Jaafar, J., Majid, Z. A., Aris, A., Umar, K., Talib, J., & Madhavi, G. (2015). Relative efficiency comparison of carboxymethyl cellulose (CMC) stabilised Fe⁰ and Fe⁰/Ag nanoparticles for rapid degradation of chlorpyrifos in aqueous solutions. *Digest Journal of Nanomaterials and Biostructures*, 10, 331–340.
- Reddy, A. V. B., Yusop, Z., Jaafar, J., Reddy, Y. V. M., Aris, A. B., Majid, Z. A., Talib, J., & Madhavi, G. (2016). Recent progress on Fe-based nanoparticles: Synthesis, properties, characterization and environmental applications. *Journal of Environmental Chemical Engineering*, 4(3), 3537–3553. <https://doi.org/10.1016/j.jece.2016.07.035>
- Reddy, A. V. B., Moniruzzaman, M., & Madhavi, G. (2020). Removal of heavy metal pollutants from wastewater using zerovalent iron nanoparticles. In *Environmental chemistry for a sustainable world* (pp. 37–72). https://doi.org/10.1007/978-3-030-52421-0_2
- Samadi, S., Lajayer, B. A., Moghiseh, E., & Rodríguez-Couto, S. (2020). Effect of carbon nanomaterials on cell toxicity, biomass production, nutritional and active compound accumulation in plants. *Environmental Technology & Innovation*, 21, 101323. <https://doi.org/10.1016/j.eti.2020.101323>
- Sarkar, M. R., Rashid, M. H., Rahman, A., Kafi, M. A., Hosen, M. I., Rahman, M. S., & Khan, M. N. (2022). Recent advances in nanomaterials based sustainable agriculture: An overview. *Environmental Nanotechnology Monitoring & Management*, 18, 100687. <https://doi.org/10.1016/j.enmm.2022.100687>
- Sharma, R. K., Kaushik, B., Yadav, S., Rana, P., Rana, P., Solanki, K., & Rawat, D. (2021). Ingeniously designed silica nanostructures as an exceptional support: Opportunities, potential challenges and future prospects for viable degradation of pesticides. *Journal of Environmental Management*, 301, 113821. <https://doi.org/10.1016/j.jenvman.2021.113821>
- Shawon, Z. B. Z., Hoque, M. E., & Chowdhury, S. R. (2020). Nanosensors and nanobiosensors: Agricultural and food technology aspects. In *Elsevier eBooks* (pp. 135–161). <https://doi.org/10.1016/b978-0-12-820702-4.00006-4>
- Sigala-Aguilar, N. A., López, M. G., & Fernández-Luqueño, F. (2024). Carbon-based nanomaterials as inducers of biocompounds in plants: Potential risks and perspectives. *Plant Physiology and Biochemistry*, 212, 108753. <https://doi.org/10.1016/j.plaphy.2024.108753>
- Sigmon, L. R., Adisa, I. O., Liu, B., Elmer, W. H., White, J. C., Dimkpa, C. O., & Fairbrother, D. H. (2021). Biodegradable polymer nanocomposites provide effective delivery and reduce phosphorus loss during plant growth. *ACS Agricultural Science & Technology*, 1(5), 529–539. <https://doi.org/10.1021/acsagagtech.1c00149>
- Singh, A., Rajput, V. D., Varshney, A., Ghazaryan, K., & Minkina, T. (2023). Small tech, big impact: Agri-nanotechnology journey to optimize crop protection and production for sustainable agriculture. *Plant Stress*, 10, 100253. <https://doi.org/10.1016/j.stress.2023.100253>
- Singh, A., Sharma, A., Singh, O., Rajput, V. D., Movsesyan, H., Minkina, T., Alexiou, A., Papadakis, M., Singh, R. K., Singh, S., Sousa, J. R., El-Ramady, H. R., Zulfikar, F., Kumar, R., Al-Ghamdi, A. A., & Ghazaryan, K. (2024). In-depth exploration of nanoparticles for enhanced nutrient use efficiency and abiotic stresses management: Present insights and future horizons. *Plant Stress*, 14, 100576. <https://doi.org/10.1016/j.stress.2024.100576>
- Soraki, R. K., Gerami, M., & Ramezani, M. (2021). Effect of graphene/metal nanocomposites on the key genes involved in rosmarinic acid biosynthesis pathway and its accumulation in *Melissa officinalis*. *BMC Plant Biology*, 21(1). <https://doi.org/10.1186/s12870-021-03052-z>

- Taloor, A. K., Sharma, S., Suryakiran, S., Sharma, R., & Sharma, M. (2024). Groundwater contamination and health risk assessment in Indian subcontinent: A geospatial approach. *Current Opinion in Environmental Science & Health*, 39, 100555. <https://doi.org/10.1016/j.coesh.2024.100555>
- Thakur, V., Sharma, S., Kumar, A., & Kumar, R. (2024). Unraveling nanoparticles efficiency in solanaceae crops: Mechanistic understanding, action, and stress mitigation approaches. *Ecological Frontiers*, 44(6), 1097–1108. <https://doi.org/10.1016/j.ecofro.2024.05.004>
- Thiruvengadam, R., Easwaran, M., Rethinam, S., Madasamy, S., Siddiqui, S. A., Kandhaswamy, A., & Venkidasamy, B. (2024). Boosting plant resilience: The promise of rare earth nanomaterials in growth, physiology, and stress mitigation. *Plant Physiology and Biochemistry*, 208, 108519. <https://doi.org/10.1016/j.plaphy.2024.108519>
- Vemula, M., & Reddy, A. V. B. (2023). Polymeric nanoparticles as effective delivery systems in agriculture sustainability. *Nanotechnology For Environmental Engineering*, 8(3), 805–814. <https://doi.org/10.1007/s41204-023-00319-8>
- Vinzant, K., Rashid, M., & Khodakovskaya, M. V. (2023). Advanced applications of sustainable and biological nano-polymers in agricultural production. *Frontiers in Plant Science*, 13. <https://doi.org/10.3389/fpls.2022.1081165>
- Wu, Q., Fan, C., Wang, H., Han, Y., Tai, F., Wu, J., Li, H., & He, R. (2023). Biphasic impacts of graphite-derived engineering carbon-based nanomaterials on plant performance: Effectiveness vs. nanotoxicity. *Advanced Agrochem*, 2(2), 113–126. <https://doi.org/10.1016/j.aac.2023.01.001>
- Yadav, A., Yadav, K., & Abd-Elsalam, K. (2023). Nanofertilizers: Types, delivery and advantages in agricultural sustainability. *Agrochemicals*, 2(2), 296–336. <https://doi.org/10.3390/agrochemicals2020019>
- Yan, Y., Zhu, X., Yu, Y., Li, C., Zhang, Z., & Wang, F. (2021). Nanotechnology strategies for plant genetic engineering. *Advanced Materials*, 34(7). <https://doi.org/10.1002/adma.202106945>
- Younes, N., Dawood, M. F., & Wardany, A. (2019). Biosafety assessment of graphene nanosheets on leaf ultrastructure, physiological and yield traits of *Capsicum annuum* L. and *Solanum melongena* L. *Chemosphere*, 228, 318–327. <https://doi.org/10.1016/j.chemosphere.2019.04.097>
- Zarrabian, M., & Sherif, S. M. (2024). Silence is not always golden: A closer look at potential environmental and ecotoxicological impacts of large-scale dsRNA application. *The Science of the Total Environment*, 950, 175311. <https://doi.org/10.1016/j.scitotenv.2024.175311>
- Zhang, E., & Liu, L. J. (2024). Iron oxide nanoparticles affect plant growth by negatively regulating soil bacterial community. *South African Journal of Botany*, 174, 410–419. <https://doi.org/10.1016/j.sajb.2024.09.018>
- Zhang, M., Ma, W., Tao, R., Fan, Q., Zhang, M., Qin, D., Cao, X., Li, J., Xiong, R., & Huang, C. (2024). Nanomaterials: Recent advances in plant disease diagnosis and treatment. *Nano Today*, 57, 102326. <https://doi.org/10.1016/j.nantod.2024.102326>

Chapter 8

Biogenic Metallic Nanoparticles: Effective Fertilizers and Fungicides in Sustainable Agriculture



Walaa R. Abdelghany

Abstract Regarding the challenges posed by climate change, rising global food demand, and declining arable land, investigating innovative agricultural practices is important. Biogenic metallic nanoparticles (BMNPs) are among the most promising technologies in sustainable agriculture due to their enormous potential as effective fungicides and fertilizers. The remarkable characteristics of BMNPs, including their large surface area, responsiveness, and controlled nutrient release, intrigue them. These nanoparticles are also more easily absorbed by plants, distributed throughout their tissues, and affect their metabolism than chemicals. These features make them ideal for enhancing plant growth and safeguarding crops against infections. For instance, their regulated delivery of nutrients can lower nutrient loss and the requirement for traditional fertilizers. The benefits of BMNPs for the environment are also noteworthy. It can contribute to a more sustainable approach to agriculture by lowering toxicity to non-target organisms and dependence on chemical inputs. Synthesis, characterization, and application of BMNPs are covered in this chapter, with a focus on improving agricultural yield and disease control. This chapter attempts to give a better understanding of how BMNPs can support sustainable farming practices by analyzing current studies and field experiences.

Keywords Biogenic nanoparticles · Nano fertilizers · Nano fungicides · Green nanomaterials · Agroecosystems

8.1 Introduction

As the demand for food increases alongside rising environmental concerns, agriculture faces the challenge of enhancing food production while lowering its ecological impact. Most of the methods used in traditional agriculture encompass the utilization of chemical fertilizers and pesticides, which results in adverse outcomes on the

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surroundings including soil erosion, contamination of water sources, and depletion of the bio-diversity (Jakhar et al., 2020). These practices can reduce soil fertility, enhance soil resistance to pests and pathogens, and pollute the environment. Therefore, concepts associated with modern agriculture include sustainable agricultural practices to improve crop yield in an environmentally friendly way (Tudi et al., 2021). In this context, nano-technology has surfaced as a prospective solution (Chhipa, 2019). Among the various innovative solutions available, biogenic metallic nanoparticles (BMNPs) stick out as particularly promising. These nanoparticles are produced with the aid of bio-organisms such as plants, bacteria, fungi, actinobacteria, or algae, which is more eco-friendly than chemical technique (Chakraborty et al., 2022). BMNPs exhibit distinct features, such as a high surface area-to-volume ratio and enhanced reactivity, which make them especially suitable for agricultural use (Das et al., 2019). The environmentally friendly biogenetic techniques employed in their production enable fine-tuning of their size and shape, thereby optimizing their performance for agricultural purposes (Alsaiani et al., 2023). Research has indicated that microbes are capable of synthesizing metal nanoparticles, including precious metals and transition elements such as gold, silver, copper, and zinc (Gahlawat & Choudhury, 2019).

Meanwhile, BMNPs serve as both fertilizers and fungicides in the agricultural application processes. As fertilizers they improve plant nutrient uptake and efficacy, diminishing the reliance on excessive chemical fertilizers (Ghosh et al., 2023a). For instance, iron oxide (Fe_2O_3) and zinc oxide assist in transforming nutrients from less accessible forms to those that plants can readily absorb (Kopittke et al., 2019). Additionally, the extensive surface area of BMNPs allows for a sluggish and continual release of nutrients, enabling growers to apply fertilizers less frequently and thereby minimizing nutrient usage (Iqbal et al., 2019). This approach has been shown to improve nutrient efficiency and lessen environmental impact. Moreover, BMNPs can enhance plant tolerance to abiotic obstacles such as drought and high salinity. This effect improves the antioxidant system of the plant, as well as the nutrition uptake during the period of stress (Abasi et al., 2022).

Conversely, BMNPs are important as fungicides providing an eco-friendly alternative to chemical fungicides. For instance, both the silver nanoparticles (AgNPs) and copper nanoparticles (CuNPs) comprise their antifungal properties by disrupting fungal cell membranes and causing oxidative stress, which eventually leading to cell mortality (Hassan et al., 2018). These nanoparticles make ROS that affects the cellular activities of pathogens and prevents their reproduction (Mai & Hilt, 2017). This oxidative stress type can efficiently manage fungal infections (Delattin et al., 2014). Various research has proved that BMNPs could impede spore germination and reduce fungal growth in several fungal pathogens hence useful in disease control (Ibrahim et al., 2020; Malik et al., 2024). Additionally, using BMNPs in agriculture aligns with the principles of sustainable farming by enhancing productivity while minimizing environmental harm. This chapter will explore the synthesis of BMNPs, the techniques used for their characterization, their mechanisms of action, and their various applications.

8.2 Biogenic Synthesis of Metallic Nanoparticles

Metal nanoparticle synthesis employs a variety of processes, which are typically divided into two categories: bottom-up and top-down (Sahoo et al., 2021). These methodologies can be further divided into chemical, physical, and biological strategies. Each approach has its strengths and weaknesses. Top-down approaches entail the fabrication of nanoparticles by reducing or dissolving larger structures or by fractal processes, while bottom-up techniques consist of the assembling of nanoparticles from atomic or molecular antecedents. Notably, these methods allow for precise control of the size and structure of the consequent nanoparticles (Satpathy et al., 2024). Top-down techniques are done by extending the particle size of a large material into that of a nanoparticle size. These methods are normally applied in the fabrication of nanoparticles in big batches but the size of the fabricated particles may not be as well controlled as with the bottom-up techniques. Biosynthesis of mineral nanoparticles employs diverse plant parts or microorganisms or both to synthesize nanoparticles (Fig. 8.1). BMNPs utilize biological protocols with specificity to develop nanoparticles with desirable properties, thereby avoiding the use of dangerous substances and diminishing expenditure and inefficiencies associated with traditional methods (Salem & Fouda, 2021).

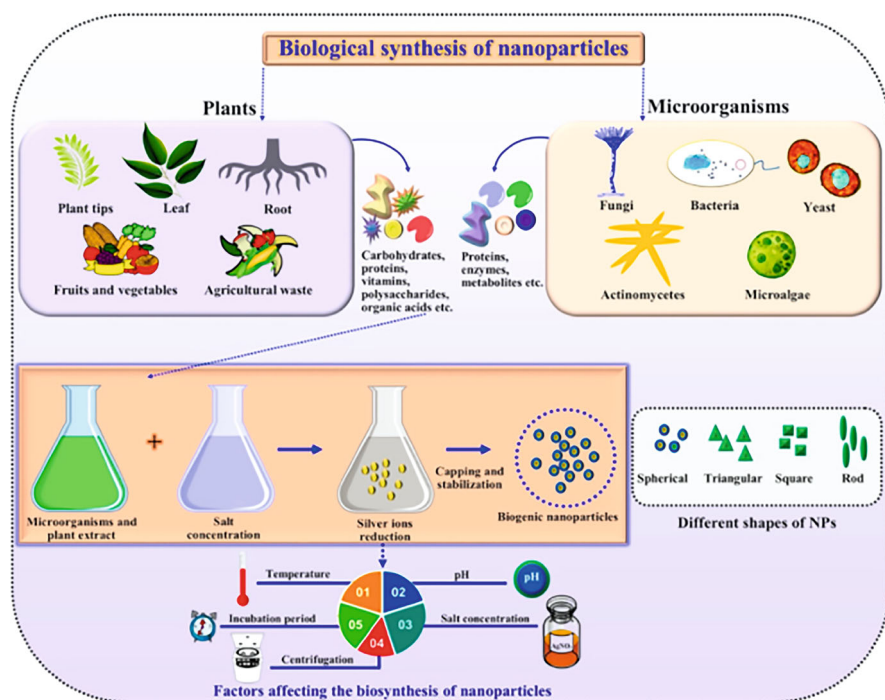


Fig. 8.1 Schematic demonstration summarizing BMNPs, their characterization, and factors affecting the green synthesis (Ali et al., 2020)

8.2.1 Plant-Mediated Synthesis

Plants are good precursors for synthesizing BMNPs because of the natural components that help reduce and stabilize metal ions (El Shafey, 2020; Dikshit et al., 2021). This process can utilize various plant elements, including leaves, stems, roots, seeds, flowers, fruits, and buds (Table 8.1). The biological synthesis of BMNPs from plants is also known as phytonanotechnology (Chakraborty et al., 2022). Within the past decade, this bio-methodology has picked up significant speed and placed itself as one of the frontiers of scientific research and applications. Phytonanotechnology has several advantages over conventional techniques (Jiang et al., 2021). It employs biological systems with the creation of nanoparticles, and the most widely used are plants, thus synthesizing a plethora of nanoparticles: metals like iron (Fe), gold (Au), platinum (Pt), silver (Ag), palladium (Pd), zinc (Zn), selenium (Se), copper (Cu), and lead (Pb) (Adeyemi et al., 2022). Plant-mediated nanoparticle fabrication could be a real prospective avenue toward sustainable agricultural practices. This synthesis, employing a green synthesis scheme, has met environmental objectives and had practical applications that improve plant endurance to stress and yield (Wang et al., 2016). The preparation of nanoparticles through plant mediation is facilitated by various phytochemicals, such as flavonoids, alkaloids, phenolics, steroids, and saponins, whichever deliver as capping delegates, stabilizers, and reducers for the nanoparticles (Hussain et al., 2016). This technique therefore offers an ecologically friendly, efficient, and low-cost technique to produce nanoparticles (Thatyana et al., 2023).

8.2.1.1 Leaf Extracts

Leaves of different plants are utilized for synthesizing nanoparticles. For instance, platinum nanoparticles synthesized from *Diospyros kaki* leaves are produced by using leaf broth at elevated temperatures to facilitate the reaction (Song et al., 2010). Generally, phytochemicals such as alkaloids, flavonoids, and phenolic compounds existing in the leaf extracts reduce and stabilize the nanoparticles (Zhang et al., 2020). In addition, extracts from *Eucalyptus globulus* and *Andrographis paniculata* leaves have been employed to synthesize lanthanum oxide and neodymium oxide nanoparticles, respectively (Sundrarajan & Muthulakshmi, 2021).

8.2.1.2 Stem Extracts

Nanoparticles can also be prepared using plant stems. For example, silver nanoparticles were fabricated by stem extract of *Coleus aromaticus* and *Salvadora persica* (Vanaja et al., 2013; Tahir et al., 2015). Zinc oxide nanoparticles (ZnO NPs) synthesized from *Swertia chirayita* showed increased photocatalytic activity and antimicrobial activity (Saha et al., 2021). Synthesizing of bimetallic iron oxide

Table 8.1 Overview of plant sources for BMNP synthesis, including size and shape characteristics

BNP type	Plant species	Plant part	Size	Shape	References
Ag	<i>Diospyros kaki</i>	Leaves	8–38	Lattice	Keskin et al. (2023)
Ag	<i>Pisum sativum</i>	Leaves	10–25	Spherical	Patra et al. (2019)
Pt	<i>Diopyros kaki</i>	Leaves	2–15	Spherical	Song et al. (2010)
Ag	<i>Nigella sativa</i>	Leaves	1–15	Spherical	Amooaghaie et al. (2015)
Ag	<i>Cotyledon orbiculata</i>	Leaves	100–140	Spherical	Tyavambiza et al. (2021)
ZnO	<i>Olea europaea</i>	Leaves	41–124	Crystal-form	Kowalczyk et al. (2011)
MgO	<i>Rosmarinus officinalis</i>	Leaves	<20	Flower-shaped	Prasad et al. (2011)
Ag	<i>Coleus aromaticus</i>	Stems	10–20	Spherical	Vanaja et al. (2013)
Ag	<i>Salvadora persica</i>	Stems	1–6	Spherical	Tahir et al. (2015)
ZnO	<i>Swertia chirayita</i>	Stems	17	Spherical	Saha et al. (2021)
Fe ₃ O ₄ -Ag	<i>Vitis vinifera</i>	Stems	<50	Spherical	Venkateswarlu et al. (2015)
Cu	<i>Syzygium aromaticum</i>	Buds	15	Sphere-shaped	Rajesh et al. (2018)
Pt	<i>Asparagus racemosus</i>	Roots	1–6	Spherical	Raut et al. (2013)
ZnO	<i>Zingiber officinale</i>	Roots	30–50	Spherical	Raj and Jayalakshmy (2015)
Ag	<i>Terminalia chebula</i>	Fruits	25	Cubic	Edison and Sethuraman (2012)
Cu	<i>Capparis spinosa</i>	Fruits	17–42	Sphere-shaped	Ebrahimi et al. (2017)
Au	<i>Citrus reticulata</i>	Fruits	15–80	Spherical	Sujitha and Kannan (2013)
Ag	<i>Prosopis farcta</i>	Fruits	10.26–14.65	Spherical	Salari et al. (2019)
Ag, Au	<i>Panax ginseng</i>	Roots	10–30, 10–40	Spherical	Singh et al. (2016)
Ag, Au	<i>Zingiber officinale</i>	Roots	10–20, 5–20	Spherical	Velmurugan et al. (2014)
TiO ₂	<i>Withania somnifera</i>	Roots	25–45	Spherical	Al-Shabib et al. (2020)
NiO	<i>Rheum turkestanicum</i>	Roots	9–18	Cubic	Saheb et al. (2019)
Ag	<i>Coffea arabica</i>	Seeds	20–30	Spherical and ellipsoidal	Dhand et al. (2016)
ZnO	<i>Peganum harmala</i>	Seeds	40	Irregular	Fazlzadeh et al. (2017)
Fe ₂ O ₃	<i>Punica granatum</i>	Seeds	25–55	Semi-spherical	Bibi et al. (2019)

(Fe₃O₄)-Ag NPs mediated by *Vitis vinifera* showed exceptional magnetic properties and reusability (Venkateswarlu et al., 2015). These nanoparticles (NPs) manifested exclusive properties arising from different phytoconstituents present in the extracts of the stems (Jayappa et al., 2020).

8.2.1.3 Root Extracts

Roots of various plants such as *Zingiber officinale* have been employed for the synthesizing of gold and silver nanoparticles, depending on their characteristics due to the reducing potential of intrinsic compounds like phenylpropanoids, ascorbic acid, and gingerol contained in the root extracts (Velmurugan et al., 2014). Nanoparticles of titanium oxide derived from the root of *Withania somnifera* exhibit considerable biological activity because of the bioactive metabolites in it as established by Al-Shabib et al., 2020. In a like manner, *Rheum turkestanicum* root extracts synthesize nickel oxide nanoparticles with a hexagonal lattice structure owed to the elevated content of anthraquinone and phenol (Saheb et al., 2019).

8.2.1.4 Fruit Extracts

Citrus reticulata, *Crataegus douglasii*, *Embllica officinalis* are some fruit extracts used to synthesize nanoparticles like gold and silver. These nanoparticles possess antibacterial, anti-inflammatory, and anticancer characteristics (Sujitha & Kannan, 2013; Ramesh et al., 2015). Extract of *Syzygium alternifolium* fruit is used for copper oxide nanoparticle synthesis with antiviral properties (Yugandhar et al., 2018).

8.2.1.5 Seed Extracts

Silver nanoparticles were also biosynthesized from seeds of *Sinapis arvensis* and *Coffea arabica* (Dhand et al., 2016) while zinc oxide and Fe₂O₃ nanoparticles were bio-produced from *Punica granatum* and *Peganum harmala* with tremendous methods of catalysis and adsorption (Fazlzadeh et al., 2017).

8.2.2 Microbial-Mediated Synthesis of Biogenic Metallic Nanoparticles

Microbial-mediated syntheses of BMNPs involve a range of microorganisms, comprising bacteria, fungi, actinobacteria, and viruses which play a crucial role in the bio-reduction and stabilization of various metal ions (Eweis et al., 2024). This green, economical, and rapid method has received much attention as a potential substitute for traditional chemical synthesis techniques. Synthetic process is relatively

uncomplicated and incorporate the incubation of microbial cultures in metal ion solutions and then through the process of centrifugation and filtration nanoparticles can be harvested. It was also observed that the size, morphological characteristics, and functional attributes of nanoparticles are conveniently regulated by factors including pH, temperature, metal concentration, and incubation time (Koul et al., 2021). Notably, microbial synthesis produces small amounts of toxic by-products hence improving the system's environmental impact. Thus, microbial-mediated synthesis is seen as the solution to the demand for environmentally friendly and more efficient synthesis processes for the enhancement of agricultural productivity with decreasing limitations given by chemical synthesis of the nanoparticles. Further, more research, which can be conducted on the conditions that make BMNPs better and the discovery of other microorganisms, can increase the impact and effectiveness of BMNPs in agriculture enabling the development of new approaches to food insecurity and crop health.

8.2.2.1 Bacteria

Most bacterial species are highly adaptable and can survive in harsh environments, including high salinity and contaminated soils. They utilize various strategies, notably efflux pumps and intracellular sequestration, to manage metal ion bioavailability for nanoparticle fabrication (Gupta et al., 2017). Furthermore, certain bacteria can convert metal ions into nanoparticles through the action of specific proteins or enzymes (Niño-Martínez et al., 2019). There are many bacteria can be employed in the synthesis of BMNPs (Table 8.2) among them several species of *Bacillus*, *Staphylococcus*, *Pseudomonas*, and *Escherichia coli* (Saeed et al., 2020). Bacteria use miscellaneous reductase enzymes to precipitate metal ions into nanoparticles. *Bacillus* spp. For instance, has been identified to fabricate silver nanoparticles (AgNPs) within the intracellular space known as periplasm (Alsamhary, 2020). *Pseudomonas stutzeri* and *Pseudomonas aeruginosa* have also shown competency in producing well-characterized silver nanoparticles (Ramadan & El-Beltagi, 2021; Abdelmoneim et al., 2022). *Stenotrophomonas* have been employed to synthesize AgNPs and AuNPs (Malhotra et al., 2013). However, it has been conceivable to use *Aeromonas hydrophila* to synthesize zinc oxide nanoparticles (ZnONPs) effectively and economically (Gaubu et al., 2023). Environmental factors in particular temperature and pH afflict the synthesis process. In particular, *Morganella psychrotolerans* synthesize spherical AgNPs at 20 °C, while at 25 °C, the synthesized nanoparticles were hexagonal, triangular, and spherical (Ramanathan et al., 2011).

8.2.2.2 Fungi

Fungal species as *Aspergillus*, *Fusarium*, and *Trichoderma* spp. are highly effective in producing BMNPs (Table 8.3) since they are capable of withstanding high concentrations of metals within their system as well as possess distinctive biosynthetic pathways (Boroumand Moghaddam et al., 2015). They can create intracellular

Table 8.2 Overview of bacterial species used to synthesize BMNPs alongside their shape, size, and applications

BNPs type	Biological agent	Shape	Size (nm)	Applications	References
Ag	<i>Bacillus subtilis</i>	Spherical	3–20	Antimicrobial	Alsamhary (2020)
Ag	<i>Bacillus zanthoxyli</i>	Polydispersed	3.68–31.60	Antimicrobial	Li et al. (2022a)
Ag	<i>Escherichia coli</i>	Spherical	5–50	Antimicrobial	Saeed et al. (2020)
Ag	<i>Enterobacter hormaechei</i>	Spherical/polydispersed	9.91–92.54	Antimicrobial	Monowar et al. (2021)
ZnO	<i>Bacillus licheniformis</i>	Nanoflowers	40	Photocatalytic degradation	Tripathi et al. (2014)
ZnO	<i>Gluconacetobacter xylinum</i>	Round to oval	38	Wound dressing	Khalid et al. (2017)
Cu	<i>Shewanella oneidensis</i>	Spherical	20–40	Wastewater biosorption	Kimber et al. (2018)
CuO	<i>Stenotrophomonas sp.</i>	Spherical	18.2–21.3	Antibacterial, antioxidant, and cytotoxic	Talebian et al. (2023)
CdS	<i>Bacillus amyloliquefaciens</i>	Cubic/hexagonal	3–4	Not specified	Singh et al. (2011)
Au	<i>Micrococcus yunnanensis</i>	Spherical	53	Antimicrobial and anticancer	Jafari et al. (2018)
Au	<i>Klebsiella pneumoniae</i>	Spherical	10–15	Antimicrobial	Prema et al. (2016)

Table 8.3 Overview of Fungi used to synthesize BMNPs alongside their shape, size, and applications

BNPs type	Biological agent	Shape	Size (nm)	Applications	References
Ag	<i>Fusarium oxysporum</i>	Spherical	5–13	Antibacterial and antitumor	Husseiny et al. (2015)
Ag	<i>Schizophyllum radiatum</i>	Spherical	10–40	Antimicrobial activity	Metuku et al. (2014)
Fe	<i>Alternaria alternata</i>	Spherical	20–40	Antimicrobial	Alamilla-Martínez et al. (2019)
Au	<i>Trichoderma harzianum</i>	Spherical	26–34	Antibacterial	Tripathi et al. (2018)
Ag	<i>Penicillium citrinum</i>	Spherical	109	Antimicrobial	Honary et al. (2013)
ZnO	<i>Aspergillus niger</i>	Hexagonal	40–60	Antibacterial	Shamim et al. (2019)

and extracellular nanoparticles by releasing enzymes and metabolites, which help diminish metal ions and remediate nanoparticles (Ghosh et al., 2021; Herrera Pérez et al., 2024). Extracellular synthesis involves adding metal precursors to fungal culture filtrates, leading to nanoparticle formation without complex methods (Li et al., 2022b; Manolescu et al., 2022). In contrast, intracellular synthesis requires the reduction of metal ions within the fungal cells, followed by nanoparticle extraction and purification (Kapoor et al., 2021). *Trichoderma viride* and *Hypocrea lixii* fungi were reported for synthesizing extracellular gold nanoparticles (Mishra et al., 2014). Similarly, *Aspergillus niger* generates spherical iron nanoparticles (FeNPs) whereas *Fusarium oxysporum* obtains zinc sulfide nanoparticles (ZnS NPs) (Youssef et al., 2017). Factors including pH, temperature, and ionic strength significantly influence the size and shape of the nanoparticles. For instance, *Fusarium oxysporum* delivers nanoparticles of varying shapes and sizes based on the growth medium's pH (Rajput et al., 2016).

8.2.2.3 Yeasts

Especially the species of *Saccharomyces cerevisiae* and *Candida* spp., have proved to be suitable synthesis nanoparticles because of their resilience to elevated concentrations of metals and the proficiency to concentrate metal ions effectively (Skalickova et al., 2017; Roychoudhury, 2020). These microorganisms employ the biomolecules existing in them, the melanin, to deposit and reduce metal ions into nanoparticles. For instance, *Yarrowia lipolytica* has been proven to have great potential in the fabrication of silver NPs (Apte et al., 2013) and *Candida utilis* agitates AgNPs with a high level of antibacterial characteristics (Waghmare et al., 2015). Besides, *Magnusiomyces ingens* is known for the green reduction of gold nanoparticles in the form of hexagons and spheres (Zhang et al., 2016), while, *Pichia pastoris* has been reported to synthesize silver nanoparticles (More et al., 2024). Nanoparticles derived from yeasts are found to be effective in environmental and agricultural applications since they are biocompatible; this shows how yeasts play a crucial duty in green nanotechnology (Shende et al., 2021).

8.2.2.4 Actinobacteria

Particularly *Streptomyces* species are highly embroiled in the synthesis of BMNPs (Table 8.4) because of their high bioactive compounds production along with their high protein content which gives them the capacity to synthesize nanoparticles effectively (Gahlawat & Choudhury, 2019). The extracellular reduction pathway is preferred due to the production of polydispersity NPs, which is beneficial in different commercial applications (Alsaiani et al., 2023). Recent studies focus on the ability of actinobacteria to synthesize various types of nanoparticles. For example, *Streptacidiphilus durhamensis*, an acidophilic actinobacterium, was exploited Buszewski et al. (2023) for fabricating spherical, stable AgNPs showing enhanced antimicrobial characteristics contrary to *Pseudomonas aeruginosa* and

Table 8.4 Overview of actinobacteria used to synthesize BMNPs alongside their shape, size, and applications

BNPs type	Biological agent	Shape	Size (nm)	Applications	References
Au	<i>Streptomyces griseoruber</i>	Spherical	5–50	Antimicrobial	Ranjitha and Rai (2017)
Ag	<i>Streptacidiphilus durhamensis</i>	Spherical	8–48	Antimicrobial	Buszewski et al. (2023)
Ag	<i>Rhodococcus</i> sp.	Spherical	10	Antimicrobial	Otari et al. (2012)
CuO	<i>Streptomyces zaomyceticus</i>	Spherical	78–80	Antimicrobial, and antioxidant	Hassan et al. (2019)
ZnONPs	<i>Streptomyces</i> strains	Hexagonal	11.76–14.58	Antimicrobial and antifungal	Rajivgandhi et al. (2022)
Au	<i>Nocardiopsis</i> sp.	Spherical	11.57	Antimicrobial	Manivasagan et al. (2015)

Staphylococcus aureus due to the stabilization and capping with bioactive molecules. Other members of Actinobacteria are also well adapted to producing gold nanoparticles (AuNPs) for instance *Thermomonospora* sp. an extremophilic actinobacterium, could produce uniform-sized AuNPs through an enzymatic process that reduces metal ions and stabilizes the nanoparticles (Ahmad et al., 2003). Moreover, *Streptomyces* strains have synthesized hexagonal and white ZnO nanoparticles (Rajivgandhi et al., 2022). While on the other hand, *Streptomyces capillispiralis* Ca-1, was employed to synthesize copper nanoparticles (CuNPs) that possessed promising antimicrobial and antifungal activity (Saad et al., 2018).

8.2.2.5 Algae

Algae have significant advantages for use in the synthesis of BMNPs because of their capability to grow in simple and minimal media and their vast assortment of biologically active compounds that can function as stabilizers and capping operatives (Table 8.5). Compounds present in algal extracts include carbohydrates, proteins, and bio-active substances such as; anti-oxidants, and pigments. These chemicals possess reducing and stabilizing properties which can be substantial in the preparation of NPs (Michalak & Chojnacka, 2015). Different types of algae ought to the biosynthesis of Ag NPs including *Sargassum plagiophyllum* synthesizing spherical Ag NPs were reported to possess antibacterial activity contrary to *E. coli* (Dhas et al., 2014). Similarly, Gold nanoparticles (AuNPs) have also been fabricated using algae; *Tetraselmis kochinensis* formed AuNPs of different dimensions (Senapati et al., 2012). Additionally, nanoparticles synthesized using *Sargassum vulgare* have been effective in managing sugar beet root rot diseases triggered by the phytopathogens *Sclerotium rolfsii*, *Rhizoctonia solani*, and *Fusarium oxysporum* (Abdelwahab et al., 2023). Meanwhile, Palladium nanoparticles (PdNPs) have been obtained using the marine alga *Sargassum bovinum* for

Table 8.5 Overview of some algae used to synthesize BMNPs alongside their shape, size, and applications

NPs type	Algal species	Shape	Size (nm)	Applications	References
Ag	<i>Sargassum plagiophyllum</i>	Spherical	21–48	Antibacterial	Dhas et al. (2014)
Ag	<i>Chlorella vulgaris</i>	Spherical	1–50	Antimicrobial	Torabfam and Yüce (2020)
Ag	<i>Portieria hornemannii</i>	Spherical	35–50	Antimicrobial	Fatima et al. (2020)
Au	<i>Padina gymnospora</i>	Spherical	53–67	Medical applications	Singh et al. (2013)
Au	<i>Turbinaria conoides</i>	Spherical	1–6	Antimicrobial	Rajeshkumar et al. (2013)
Pd	<i>Sargassum bovinum</i>	Octahedral	5–10	Bioremediation	Momeni and Nabipour (2015)
PdNPs	<i>Chlorella vulgaris</i>	Spherical	5–20	Antimicrobial	Arsiya et al. (2017)
ZnONPs	<i>Padina tetrastromatica</i>	Spherical	16–30	Antimicrobial and photocatalytic	Pandimurugan and Thambidurai (2016)
ZnONPs	<i>Chlorella vulgaris</i>	Nanorods	21	UV protection and antibacterial properties	Taghizadeh et al. (2020)
Fe ₃ O ₄	<i>Sargassum acinarium</i>	Spherical	21.6–27.4	Bioremediation	El-Kassas et al. (2016)

bioremediation applications (Momeni & Nabipour, 2015). Furthermore, *Chlorella vulgaris* derived ZnO nanorods also revealed significant UV blockage and appealing antibacterial features (Taghizadeh et al., 2020). *Sargassum acinarium* and *Padina pavonica*-mediated iron oxide nanoparticles are effective in bioremediation processes, particularly for removing heavy metals from contaminated areas (El-Kassas et al., 2016).

8.3 Characterization of Biogenic Metallic Nanoparticles

Characterization of BMNPs is critical for interpretation their properties and attitude of these BMNPs. Various methods are used to determine their size, shape, and surface chemistry or composition.

8.3.1 Scanning Electron Microscopy (SEM)

SEM gives a realized image of the surface topography of nanoparticles in a high-magnification view. In addition, it delivers information about the shape, size, and

distribution of BMNPs (Metryka et al., 2024). For instance, the SEM images of the synthesized silver nanoparticles extracted from the plant demonstrate the spherical and cubic morphology with a size distribution of about 48.5 nm (Lu et al., 2022).

8.3.2 Transmission Electron Microscopy (TEM)

Through the TEM it is possible to get high settlement in assessing the internal shape and size of NPs. It gives the images at the nanometric scale necessary for the evaluation of the crystal structure and dispersion of BMNPs (Balu et al., 2022). TEM images of gold nanoparticles also capture the crystalline nature of the particles depicting sufficient mono-dispersed, spherical, and almost the size distribution of around 35 nm (Chen et al., 2022).

8.3.3 X-Ray Diffraction (XRD) Pattern

XRD is employed in the identification of the phase and crystal structure of nanoparticles. It gives detailed description on the size, form, and orientation of the nanoparticles' crystalline realms (Haque et al., 2022). Zinc oxide nanoparticle samples subjected to XRD show diffraction peaks which confirms the crystalline behavior of the particles (Kumar & Seth, 2021).

8.3.4 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR assay reveals the kind of functional groups present at the surface of BMNPs and helps to understand the interaction between nanoparticles and stabilizing agents. This improves the evaluation of the chemical surroundings existing around the nanoparticles (Mani et al., 2021). From FTIR spectra of the synthesized silver nanoparticles using plant extracts, numerous functional groups associated with nanoparticle stabilization are identified (Soliman et al., 2022).

8.4 Biogenic Metallic Nanoparticles Used as Fertilizers

Biogenic metallic nanoparticles (BMNPs) represent a revolutionary approach in agricultural fertilization, addressing challenges in nutrient delivery, soil health, and crop yield through environmentally friendly biological synthesis (Verma et al., 2022). They enhance the solubility and bioavailability of nutrients, improving soil characteristics while minimizing adverse environmental impacts. BMNPs enable

slow and controlled nutrient release, increasing absorption rates and reducing nutrient leaching, particularly for those nutrients susceptible to loss (Kopittke et al., 2019).

Furthermore, BMNPs strengthen soil health by enhancing its physical and chemical properties, such as nutrient-holding capacity and adsorption (Fayiga & Saha, 2017). They also promote microbial activity, which is crucial for nutrient cycling and soil fertility, contributing to more balanced and sustainable soil ecosystems (Javed et al., 2019). Overall, BMNPs provide a superior alternative to conventional fertilizers, reducing environmental damage without compromising plant growth and productivity. This reduction in fertilizer use may also help mitigate greenhouse gas emissions and the occurrence of deleterious algal blooming in water bodies (Jha et al., 2023).

BMNPs can be absorbed by plants through soil or foliar application, entering via roots or leaves and moving through the xylem or phloem to distribute nutrients. This process enhances crop growth, quality, and yield due to effective nutrient delivery mechanisms (Fig. 8.2). Various field studies indicate that crops treated with BMNPs exhibit improved growth parameters, increased biomass accumulation, and higher yields. Zinc oxide nanoparticles, for example, have been demonstrated to improve rice yield and quality by alleviating zinc deficiencies by stimulating enzyme

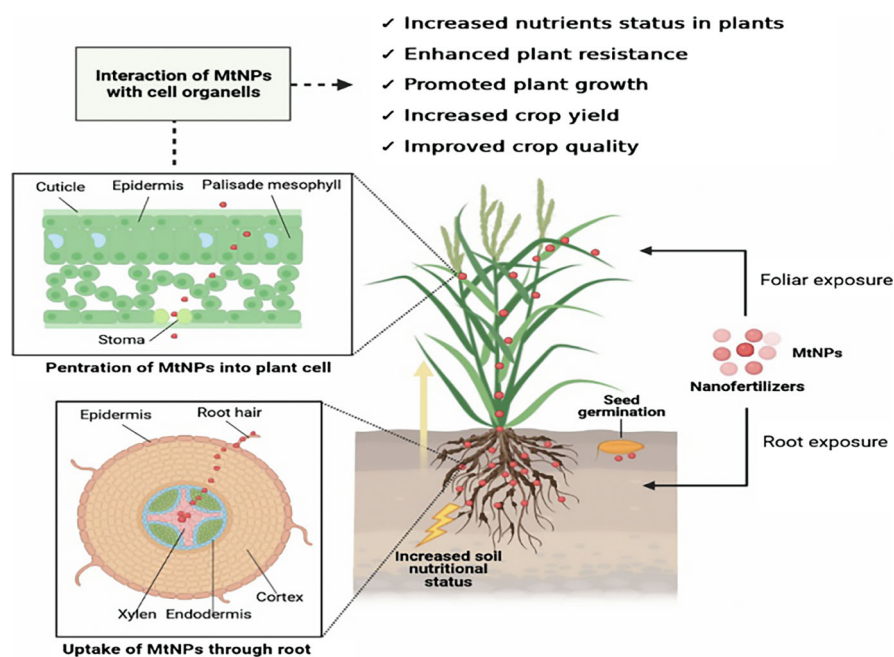


Fig. 8.2 Schematic representation of the uptake and translocation of biogenic metallic nanoparticles in plants via soil and roots as nanofertilizers, along with their potential impact on plant growth (Bahrulolum et al., 2021)

activities and regulating oxidative stress genes (Prakash et al., 2022). Biogenic ZnO nanoparticles are particularly effective in managing zinc deficiencies, which leading to lessened growth, lower tillering, chlorosis, and poverty wheat attribute (Zafar et al., 2018). Zinc is vital for enzymatic activities essential for plant health, influencing key metabolic enzymes, hydrogenase, and carbonic anhydrase (Al Jabri et al., 2022). Additionally, foliar applications of nano Zn fertilizers significantly enhance physiological processes in cotton, increasing chlorophyll content and boosting antioxidant enzyme activities (Rezaei & Abbasi, 2014). Overall, biogenic ZnO nanoparticles improve zinc availability, enhancing enzyme activity, promoting plant growth, and resulting in healthier crops with better yields (Azam et al., 2022).

Iron oxide nanoparticles have also proven effective in addressing iron deficiencies in agricultural soils, enhancing plant health and productivity (Yousaf et al., 2023). Iron is essential for chlorophyll synthesis, photosynthesis, and various physiological processes (Rui et al., 2016). Deficiencies can lead to significant morphological changes, such as root tip swelling and altered lateral root development in cotton, which can hinder iron absorption (Kanjana, 2019). Both foliar and root applications of biogenic Fe₂O₃ nano fertilizers increase chlorophyll content and improve maize performance with reduced fertilizer usage (Yousaf et al., 2023). They also enhance iron availability in deficient soils, helping to alleviate iron deficiency symptoms and improve growth factors and crop productivity (Li et al., 2021).

Copper is a crucial micronutrient that contributes to various physiological processes in plants, including photosynthesis and respiration (Wang et al., 2019). Biogenic CuO nanoparticles effectively address copper deficiencies in the soil, enhancing plant growth by improving disease resistance and stress tolerance (Leonardi et al., 2021). These nanoparticles restore bioavailable copper levels, which supports plant development and boosts resilience against environmental challenges, ultimately resulting in improved crop yields and health (Ibrahim et al., 2022). For instance, research by Deng et al. (2022) demonstrated that CuO nanoparticles led to increased yield, nutritional quality, and auxin-related gene expression in both wild and cultivated rice.

Silver nanoparticles (AgNPs) are also recognized for their antimicrobial properties and ability to enhance plant growth (Khan et al., 2023). They improve nutrient acquisition through root structures and boost stress tolerance against unfavorable conditions like water deficit and high salinity (Abasi et al., 2022). Additionally, AgNPs protect plants from pathogens, thereby maintaining plant health and increasing crop productivity (Anand & Bhagat, 2019). Their multifunctional capabilities make them valuable in agriculture for developing more resilient crops (Ghosh et al., 2023a, b).

Titanium dioxide nanoparticles (TiO₂ NPs) enhance plant growth and productivity by improving photosynthetic capacity and nitrogen metabolism. Research indicates that nanosized TiO₂ boosts growth rates and chlorophyll levels in various plants, enhancing photosynthetic efficiency. Furthermore, TiO₂ NPs improve drought tolerance and grain yield in sweet corn, with effects linked to their role in the thylakoid membrane for efficient light energy capture and conversion (Karvar et al., 2022).

8.5 Biogenic Metallic Nanoparticles as Fungicides

Food security is threatened by diseases that reduce crop yields, affecting about one-third of global production annually (Rizzo et al., 2021). Traditional chemical agents like bactericides, fungicides, and nematicides, while effective against plant diseases, often harm the environment and non-target organisms. Their excessive use can lead to pathogen resistance and pose health risks (Gikas et al., 2022).

In contrast, nanobiotechnology, particularly biogenic metallic nanoparticles (BMNPs) made from natural materials, offers a more successful and ecologically friendly disposition (Kumar et al., 2023). For instance, selenium nanoparticles (SeNPs) exhibit positive effects on crop yield and sustainability by mitigating pathogen impacts (Mikhailova, 2023).

BMNPs present numerous interests over conventional fungicides, in particular, heightened efficiency due to their larger surface area, reduced risk of pathogen resistance, minimal ecological toxicity, and enhanced biodegradability (Ghosh et al., 2023a, b). Additionally, they help improve plant health and boost crop productivity, making them a sustainable choice for agriculture (Choudhary et al., 2022).

Biogenic silver nanoparticles (AgNPs) are recognized for their strong antifungal activeness, which operates through multiple mechanisms. They disrupt fungal cell membranes, triggering cell swelling and leakage of internal contents, ultimately harming fungal survival (Bruna et al., 2021). Furthermore, AgNPs generate reactive oxygen species (ROS), thereby superoxide anions and hydrogen peroxide, leading to oxidative stress, cellular damage, DNA damage, and eventual fungal cell death (Chatterjee et al., 2024). They effectively interfere with fungal enzymes necessary for metabolic processes and demonstrate a broad spectrum of activity contrary to diverse pathogenic fungi (Khalil et al., 2019). AgNPs are particularly valuable in managing fungal diseases due to their ability to disrupt cellular components (Gupta & Saxena, 2023). Furthermore, their biogenic synthesis from renewable sources produces fewer toxic byproducts, making them environmentally friendly antifungal option compared to conventional chemical agents. For instance, AgNPs synthesized from leaf extracts significantly inhibited the progress of phytopathogenic fungi like *Penicillium*, *Fusarium*, and *Aspergillus* through mechanisms such as anti-adherence activity and compromised membrane integrity (Haroon et al., 2019).

Biogenic zinc oxide nanoparticles (ZnO NPs), derived from plant extracts or microorganisms, are also cost-effective and less hazardous than chemically synthesized alternatives. They exhibit strong antifungal properties through various mechanisms, including inhibition of cell walls, disruption of cell membranes, and alterations in cell membrane fluidity (He et al., 2011). ZnO NPs generate ROS, leading to oxidative stress and modifications of lipids, proteins, and DNA, ultimately affecting mitochondrial function (Li et al., 2017). They can disrupt critical biological functions by interacting with proteins and DNA (Gudkov et al., 2021), resulting in significant changes in hyphal shape and size and reducing spore formation (Sharma

et al., 2023). For example, ZnO NPs manufactured from *Terminalia bellerica* showed notable antifungal activeness contrary to *Alternaria brassicae* at a concentration of 200 ppm (Dhiman et al., 2022). Additionally, they can modulate stress gene expression, enhancing their antifungal efficacy (Sun et al., 2018). Their biogenic synthesis contributes to reduced toxicity, making them an eco-friendly solution for controlling fungal diseases (Gur et al., 2022).

Biogenic copper nanoparticles (CuNPs) effectively manage a range of pathogenic fungi by generating reactive oxygen species that disrupt fungal cellular components and functions (Maqsood et al., 2023). Additionally, they can form chelates with essential elements necessary for metabolism and interfere with key enzymes, leading to fungal growth inhibition. These nanoparticles have proven effective against multiple fungal species and can be applied to soil or used in plant treatments to achieve optimal disease control (Moflikoane, 2015; Ingle et al., 2020). For instance, CuNPs fabricated from endophytic *Streptomyces capillispiralis* and *Streptomyces griseus* prepared from citron juice (*Citrus medica* Linn.), exhibited strong antifungal potentialities against many fungi such as; *Alternaria* spp., *Pectinophora cossortella*, *A. niger*, *Pythium* spp., and *Fusarium* spp. (Hassan et al., 2018; Ponmurugan et al., 2016). Likewise, CuNPs incorporated with copper oxychloride showed the best results against *Phytophthora cinnamomi* and *Alternaria alternata* (Banik & Pérez-de-Luque, 2017). Furthermore, copper oxide nanoparticles (CuO NPs) are effective in managing diseases such as blight, rust and root rot and enhancing crop health (Farooq et al., 2022). Therefore, these findings demonstrate the prospect of CuNPs for developing green nano-copper-fungicides in agriculture.

8.6 Conclusion

Biogenic metallic nanoparticles (BMNPs) present sustainable strategies for enhancing nutrient efficiency, soil health, and disease management. These natural organo-metallic nanoparticles, derived from plant extracts and microorganisms, offer several advantages over traditional chemical methods. They aid in nutrient retention, reduce fertilizer requirements, and help prevent soil degradation by promoting beneficial structural arrangements and improving microbial health. BMNPs are effective in tackling pathogen resistance and environment contamination problems and demonstrating great antifungal activity and low toxicity.

Future research directions should focus on developing large-scale production techniques, optimizing the synthesis of BMNPs to lower costs, and understanding their interactions with various soil types and plant organisms. The combination of nanotechnology and precision agriculture may further enhance the application of BMNPs in farming practices, providing sustainable solutions to current and future food security challenges. Investigating the long-term implications and principles of BMNPs will be crucial for optimizing their use while minimizing negative impacts.

References

- Abasi, F., Raja, N. I., Mashwani, Z. U. R., Amjad, M. S., Ehsan, M., Mustafa, N., et al. (2022). Biogenic silver nanoparticles as a stress alleviator in plants: A mechanistic overview. *Molecules*, 27(11), 3378.
- Abdelmoneim, H. M., Taha, T. H., Elnouby, M. S., & AbuShady, H. M. (2022). Extracellular biosynthesis, OVAT/statistical optimization, and characterization of silver nanoparticles (AgNPs) using *Leclercia adecarboxylata* THHM and its antimicrobial activity. *Microbial Cell Factories*, 21(1), 277.
- Abdelwahab, N., Rabie, W., & Mohamed, F. (2023). Fabrication and characterization of novel biocomposite based on *Sargassum vulgare* for controlling sugar beet root diseases. *Chemical and Biological Technologies in Agriculture*, 10(1), 52.
- Adeyemi, J. O., Oriola, A. O., Onwudiwe, D. C., & Oyedeji, A. O. (2022). Plant extracts mediated metal-based nanoparticles: Synthesis and biological applications. *Biomolecules*, 12(5), 627.
- Ahmad, A., Senapati, S., Khan, M. I., Kumar, R., Ramani, R., Srinivas, V., et al. (2003). Intracellular synthesis of gold nanoparticles by a novel alkalotolerant actinomycete, *Rhodococcus* species. *Nanotechnology*, 14(7), 824–828.
- Al Jabri, H., Saleem, M. H., Rizwan, M., Hussain, I., Usman, K., & Alsafran, M. (2022). Zinc oxide nanoparticles and their biosynthesis: Overview. *Life*, 12(4), 594.
- Alamilla-Martínez, D. G., Rojas-Avelizapa, N. G., Domínguez-López, I., Pool, H., Gómez-Ramírez, M., & de Querétaro, A. (2019). Biosynthesis of iron nanoparticles (FeNPs) by *Alternaria alternata* MVSS-AH-5. *Mexican Journal Of Biotechnology*, 1, 1–4.
- Ali, M. A., Ahmed, T., Wu, W., Hossain, A., Hafeez, R., Islam Masum, M. M., et al. (2020). Advancements in plant and microbe-based synthesis of metallic nanoparticles and their antimicrobial activity against plant pathogens. *Nanomaterials*, 10(6), 1146.
- Alsaari, N. S., Alzahrani, F. M., Amari, A., Osman, H., Harharah, H. N., Elboughdiri, N., & Tahoon, M. A. (2023). Plant and microbial approaches as green methods for the synthesis of nanomaterials: Synthesis, applications, and future perspectives. *Molecules*, 28(1), 463.
- Alsamhary, K. I. (2020). Eco-friendly synthesis of silver nanoparticles by *Bacillus subtilis* and their antibacterial activity. *Saudi Journal of Biological Sciences*, 27(8), 2185–2191.
- Al-Shabib, N. A., Husain, F. M., Qais, F. A., Ahmad, N., Khan, A., Alyousef, A. A., et al. (2020). Phyto-mediated synthesis of porous titanium dioxide nanoparticles from *Withania somnifera* root extract: Broad-spectrum attenuation of biofilm and cytotoxic properties against HepG2 cell lines. *Frontiers in Microbiology*, 11, 1680.
- Amooaghaie, R., Saeri, M. R., & Azizi, M. (2015). Synthesis, characterization and biocompatibility of silver nanoparticles synthesized from *Nigella sativa* leaf extract in comparison with chemical silver nanoparticles. *Ecotoxicology and Environmental Safety*, 120, 400–408.
- Anand, R., & Bhagat, M. (2019). Silver nanoparticles (AgNPs): As nanopesticides and nanofertilizers. *MOJ Biology Medicine*, 4(1), 19–20.
- Apte, M., Sambre, D., Gaikawad, S., Joshi, S., Bankar, A., Kumar, A. R., & Zinjarde, S. (2013). Psychrotrophic yeast *Yarrowia lipolytica* NCYC 789 mediates the synthesis of antimicrobial silver nanoparticles via cell-associated melanin. *AMB Express*, 3, 1–8.
- Arsiya, F., Sayadi, M. H., & Sobhani, S. (2017). Green synthesis of palladium nanoparticles using *Chlorella vulgaris*. *Materials Letters*, 186, 113–115.
- Azam, M., Bhatti, H. N., Khan, A., Zafar, L., & Iqbal, M. (2022). Zinc oxide nano-fertilizer application (foliar and soil) effect on the growth, photosynthetic pigments and antioxidant system of maize cultivar. *Biocatalysis and Agricultural Biotechnology*, 42, 102343.
- Bahrulolum, H., Nooraei, S., Javanshir, N., Tarrahimofrad, H., Mirbagheri, V. S., Easton, A. J., & Ahmadian, G. (2021). Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector. *Journal of Nanobiotechnology*, 19, 1–26.
- Balu, S. K., Andra, S., Damiri, F., Sivaramalingam, A., Sudandaradoss, M. V., Kumarasamy, K., et al. (2022). Size-dependent antibacterial, antidiabetic, and toxicity of silver nanoparticles synthesized using solvent extraction of *Rosa indica* L. Petals. *Pharmaceuticals*, 15(6), 689.

- Banik, S., & Pérez-de-Luque, A. (2017). In vitro effects of copper nanoparticles on plant pathogens, beneficial microbes and crop plants. *Spanish Journal of Agricultural Research*, 15(2), e1005.
- Bibi, I., Nazar, N., Ata, S., Sultan, M., Ali, A., Abbas, A., et al. (2019). Green synthesis of iron oxide nanoparticles using pomegranate seeds extract and photocatalytic activity evaluation for the degradation of textile dye. *Journal of Materials Research and Technology*, 8(6), 6115–6124.
- Boroumand Moghaddam, A., Namvar, F., Moniri, M., Tahir, M., & P., Azizi, S., & Mohamad, R. (2015). Nanoparticles biosynthesized by fungi and yeast: A review of their preparation, properties, and medical applications. *Molecules*, 20(9), 16540–16565.
- Bruna, T., Maldonado-Bravo, F., Jara, P., & Caro, N. (2021). Silver nanoparticles and their antibacterial applications. *International Journal of Molecular Sciences*, 22(13), 7202.
- Buszewski, B., Railean-Plugaru, V., Pomastowski, P., Rafińska, K., Szultka-Mlynska, M., Golinska, P., et al. (2023). Antimicrobial activity of biosilver nanoparticles produced by a novel *Streptacidiphilus* strain. *Journal of Basic Microbiology*, 63(1), 64–74.
- Chakraborty, S., Singh, A., & Roychoudhury, A. (2022). Biogenic nanoparticles and generation of abiotic stress-resilient plants: A new approach for sustainable agriculture. *Plant Stress*, 6, 100117.
- Chatterjee, N., Pal, S., & Dhar, P. (2024). Green silver nanoparticles from bacteria-antioxidant, cytotoxic and antifungal activities. *Next Nanotechnology*, 6, 100089.
- Chen, Q., Gu, P., Liu, X., Hu, S., Zheng, H., Liu, T., & Li, C. (2022). Gold nanoparticles encapsulated resveratrol as an anti-aging agent to delay cataract development. *Pharmaceuticals*, 16(1), 26.
- Chhipa, H. (2019). Applications of nanotechnology in agriculture. In *Methods in microbiology* (Vol. 46, pp. 115–142). Academic Press.
- Choudhary, M., Jones, J. B., & Paret, M. L. (2022). Natural or green synthesis nanomaterials and impact on plant pathogens. In *Nanotechnology-based sustainable alternatives for the management of plant diseases* (pp. 5–29). Elsevier.
- Das, G., Patra, J. K., Paramithiotis, S., & Shin, H. S. (2019). The sustainability challenge of food and environmental nanotechnology: Current status and imminent perceptions. *International Journal of Environmental Research and Public Health*, 16(23), 4848.
- Delatin, N., Cammue, B. P., & Thevissen, K. (2014). Reactive oxygen species-inducing antifungal agents and their activity against fungal biofilms. *Future Medicinal Chemistry*, 6(1), 77–90.
- Deng, C., Wang, Y., Navarro, G., Sun, Y., Cota-Ruiz, K., Hernandez-Viezcas, J. A., et al. (2022). Copper oxide (CuO) nanoparticles affect yield, nutritional quality, and auxin associated gene expression in weedy and cultivated rice (*Oryza sativa* L.) grains. *Science of the Total Environment*, 810, 152260.
- Dhand, V., Soumya, L., Bharadwaj, S., Chakra, S., Bhatt, D., & Sreedhar, B. (2016). Green synthesis of silver nanoparticles using *Coffea arabica* seed extract and its antibacterial activity. *Materials Science & Engineering: C, Materials for Biological Applications*, 58, 36–43.
- Dhas, S. T., Kumar, P. S., Rajeshkumar, S., & Aiswarya, S. (2014). Green synthesis of silver nanoparticles from marine algae *Sargassum plagiophyllum* and its antibacterial activity against *E. coli*. *Journal of Nanostructure in Chemistry*, 4(1), 1–10.
- Dhiman, S., Varma, A., Prasad, R., & Goel, A. (2022). Mechanistic insight of the antifungal potential of green synthesized zinc oxide nanoparticles against *Alternaria brassicae*. *Journal of Nanomaterials*, 2022(1), 7138843.
- Dikshit, P. K., Kumar, J., Das, A. K., Sadhu, S., Sharma, S., Singh, S., et al. (2021). Green synthesis of metallic nanoparticles: Applications and limitations. *Catalysts*, 11(8), 902.
- Ebrahimi, K., Shiravand, S., & Mahmoudvand, H. (2017). Biosynthesis of copper nanoparticles using aqueous extract of *Capparis spinosa* fruit and investigation of its antibacterial activity. *Marmara Pharmaceutical Journal*, 21(4), 866–871.
- Edison, T. J. I., & Sethuraman, M. G. (2012). Instant green synthesis of silver nanoparticles using *Terminalia chebula* fruit extract and evaluation of their catalytic activity on reduction of methylene blue. *Process Biochemistry*, 47(9), 1351–1357.

- El Shafey, A. M. (2020). Green synthesis of metal and metal oxide nanoparticles from plant leaf extracts and their applications: A review. *Green Processing and Synthesis*, 9(1), 304–339.
- El-Kassas, H. Y., Aly-Eldeen, M. A., & Gharib, S. M. (2016). Green synthesis of iron oxide (Fe₃O₄) nanoparticles using two selected brown seaweeds: Characterization and application for lead bioremediation. *Acta Oceanologica Sinica*, 35, 89–98.
- Eweis, A. A., El-Raheem, H. A., Ahmad, M. S., Hozzein, W. N., & Mahmoud, R. (2024). Green fabrication of nanomaterials using microorganisms as nano-factories. *Journal of Cluster Science*, 35(7), 1–28.
- Farooq, M. A., Hannan, F., Islam, F., Ayyaz, A., Zhang, N., Chen, W., et al. (2022). The potential of nanomaterials for sustainable modern agriculture: Present findings and future perspectives. *Environmental Science: Nano*, 9(6), 1926–1951.
- Fatima, R., Priya, M., & Indurthi, L. (2020). Biosynthesis of silver nanoparticles using red algae *Portieria hornemannii* and its antibacterial activity against fish pathogens. *Microbial Pathogenesis*, 138, 103780.
- Fayiga, A. O., & Saha, U. K. (2017). Nanoparticles in biosolids: Effect on soil health and crop growth. *Peertechz Journal of Environmental Science and Toxicology*, 2(1), 059–067.
- Fazlzadeh, M., Khosravi, R., & Zarei, A. (2017). Green synthesis of zinc oxide nanoparticles using *Peganum harmala* seed extract, and loaded on *Peganum harmala* seed powdered activated carbon as new adsorbent for removal of Cr (VI) from aqueous solution. *Ecological Engineering*, 103, 180–190.
- Gahlawat, G., & Choudhury, A. R. (2019). A review on the biosynthesis of metal and metal salt nanoparticles by microbes. *RSC Advances*, 9(23), 12944–12967.
- Gaubha, A., Hari, S. K., Ramamoorthy, V., Vellasamy, S., Govindan, G., & Arasu, M. V. (2023). The versatility of green synthesized zinc oxide nanoparticles in sustainable agriculture: A review on metal-microbe interaction that rewards agriculture. *Physiological and Molecular Plant Pathology*, 125, 102023.
- Ghosh, S., Shah, S., & Webster, T. J. (2021). Recent trends in fungal biosynthesis of nanoparticles. In *Fungi bio-prospects in sustainable agriculture, environment and nano-technology* (pp. 403–452). Academic Press.
- Ghosh, D., Sarkar, M. M., & Roy, S. (2023a). Smart fertilizers: The prospect of slow release nanofertilizers in modern agricultural practices. In *Nanofertilizers for sustainable agroecosystems: Recent advances and future trends* (pp. 343–372). Cham.
- Ghosh, S., Mondol, S., Lahiri, D., Nag, M., Sarkar, T., Pati, S., et al. (2023b). Biogenic silver nanoparticles (AgNPs) from *Tinosporacordifolia* leaves: An effective antibiofilm agent against *Staphylococcus aureus* ATCC 23235. *Frontiers in Chemistry*, 11, 1118454.
- Gikas, G. D., Parlakidis, P., Mavropoulos, T., & Vryzas, Z. (2022). Particularities of fungicides and factors affecting their fate and removal efficacy: A review. *Sustainability*, 14(7), 4056.
- Gudkov, S. V., Burmistrov, D. E., Serov, D. A., Rebezov, M. B., Semenova, A. A., & Lisitsyn, A. B. (2021). A mini review of antibacterial properties of ZnO nanoparticles. *Frontiers in Physics*, 9, 641481.
- Gupta, T., & Saxena, J. (2023). Biogenic synthesis of silver nanoparticles from *Aspergillus oryzae* mtcc 3107 against plant pathogenic fungi *Sclerotinia sclerotiorum* mtcc 8785. *Journal of Microbiology, Biotechnology and Food Sciences*, 12(4), e9387–e9387.
- Gupta, D., Singh, A., & Khan, A. U. (2017). Nanoparticles as efflux pump and biofilm inhibitor to rejuvenate bactericidal effect of conventional antibiotics. *Nanoscale Research Letters*, 12(1), 454.
- Gur, T., Meydan, I., Seckin, H., Bekmezci, M., & Sen, F. (2022). Green synthesis, characterization and bioactivity of biogenic zinc oxide nanoparticles. *Environmental Research*, 204, 111897.
- Haque, S., Faidah, H., Ashgar, S. S., Abujamel, T. S., Mokhtar, J. A., Almuhayawi, M. S., et al. (2022). Green synthesis of Zn (OH) 2/ZnO-based bionanocomposite using pomegranate peels and its application in the degradation of bacterial biofilm. *Nanomaterials*, 12(19), 3458.
- Haroon, M., Zaidi, A., Ahmed, B., Rizvi, A., Khan, M. S., & Musarrat, J. (2019). Effective inhibition of phytopathogenic microbes by eco-friendly leaf extract mediated silver nanoparticles (AgNPs). *Indian Journal of Microbiology*, 59, 273–287.

- Hassan, S. E. D., Salem, S. S., Fouda, A., Awad, M. A., El-Gamal, M. S., & Abdo, A. M. (2018). New approach for antimicrobial activity and bio-control of various pathogens by biosynthesized copper nanoparticles using endophytic actinomycetes. *Journal of Radiation Research and Applied Sciences*, 11(3), 262–270.
- Hassan, S. E. D., Fouda, A., Radwan, A. A., Salem, S. S., Barghoth, M. G., Awad, M. A., et al. (2019). Endophytic actinomycetes *Streptomyces* spp mediated biosynthesis of copper oxide nanoparticles as a promising tool for biotechnological applications. *JBIC Journal of Biological Inorganic Chemistry*, 24, 377–393.
- He, L., Liu, Y., Mustapha, A., & Lin, M. (2011). Antifungal activity of zinc oxide nanoparticles against *Botrytis cinerea* and *Penicillium expansum*. *Microbiological Research*, 166(3), 207–215.
- Herrera Pérez, G. M., Castellano, L. E., & Ramírez Valdespino, C. A. (2024). Trichoderma and mycosynthesis of metal nanoparticles: Role of their secondary metabolites. *Journal of Fungi*, 10(7), 443.
- Honary, S., Barabadi, H., Gharaei-Fathabad, E., & Naghibi, F. (2013). Green synthesis of silver nanoparticles induced by the fungus *penicillium citrinum*. *Tropical Journal of Pharmaceutical Research*, 12(1), 7–11.
- Hussain, I., Singh, N. B., Singh, A., Singh, H., & Singh, S. C. (2016). Green synthesis of nanoparticles and its potential application. *Biotechnology Letters*, 38, 545–560.
- Husseiny, S. M., Salah, T. A., & Anter, H. A. (2015). Biosynthesis of size controlled silver nanoparticles by *Fusarium oxysporum*, their antibacterial and antitumor activities. *Beni-Suef University Journal of Basic and Applied Sciences*, 4(3), 225–231.
- Ibrahim, S., Ahmad, Z., Manzoor, M. Z., Mujahid, M., Faheem, Z., & Adnan, A. (2020). Optimization for biogenic microbial synthesis of silver nanoparticles through response surface methodology, characterization, their antimicrobial, antioxidant, and catalytic potential. *Scientific Reports*, 11(1), 770.
- Ibrahim, A. S., Ali, G. A., Hassanein, A., Attia, A. M., & Marzouk, E. R. (2022). Toxicity and uptake of CuO nanoparticles: Evaluation of an emerging nanofertilizer on wheat (*Triticum aestivum* L.) plant. *Sustainability*, 14(9), 4914.
- Ingle, A. P., Biswas, A., Vanlalveni, C., Lalfakzuala, R., Gupta, I., Ingle, P., et al. (2020). Biogenic synthesis of nanoparticles and their role in the management of plant pathogenic fungi. In *Microbial nanotechnology* (pp. 135–161). CRC Press.
- Iqbal, M., Umar, S., & Mahmooduzzafar, F. (2019). Nano-fertilization to enhance nutrient use efficiency and productivity of crop plants. In *Nanomaterials and plant potential* (pp. 473–505). Springer.
- Jafari, M., Rokhbakhsh-Zamin, F., Shakibaie, M., Moshafi, M. H., Ameri, A., Rahimi, H. R., & Forootanfar, H. (2018). Cytotoxic and antibacterial activities of biologically synthesized gold nanoparticles assisted by *Micrococcus yunnanensis* strain J2. *Biocatalysis and Agricultural Biotechnology*, 15, 245–253.
- Jakhar, S. R., Singh, J., Kumhar, B. L., & Kumar, V. (2020). Soil microbes: A key player on soil health and crop production under changing climate. *Progressive Agriculture*, 20(1and2), 129–140.
- Javed, Z., Dashora, K., Mishra, M., Fasake, V. D., & Srivastva, A. (2019). Effect of accumulation of nanoparticles in soil health-a concern on future. *Frontiers in Nanoscience and Nanotechnology*, 5(1), 1–9.
- Jayappa, M. D., Ramaiah, C. K., Kumar, M. A. P., Suresh, D., Prabhu, A., Devasya, R. P., & Sheikh, S. (2020). Green synthesis of zinc oxide nanoparticles from the leaf, stem and in vitro grown callus of *Mussaenda frondosa* L.: Characterization and their applications. *Applied Nanoscience*, 10, 3057–3074.
- Jha, A., Pathania, D., Damathia, B., Raizada, P., Rustagi, S., Singh, P., et al. (2023). Panorama of biogenic nano-fertilizers: A road to sustainable agriculture. *Environmental Research*, 235, 116456.

- Jiang, M., Song, Y., Kanwar, M. K., Ahammed, G. J., Shao, S., & Zhou, J. (2021). Phytonanotechnology applications in modern agriculture. *Journal of Nanobiotechnology*, 19, 1–20.
- Kanjana, D. (2019). Foliar study on effect of iron oxide nanoparticles as an alternate source of iron fertilizer to cotton. *International Journal of Chemical Studies*, 7(3), 4374–4379.
- Kapoor, R. T., Salvadori, M. R., Rafatullah, M., Siddiqui, M. R., Khan, M. A., & Alshareef, S. A. (2021). Exploration of microbial factories for synthesis of nanoparticles—a sustainable approach for bioremediation of environmental contaminants. *Frontiers in Microbiology*, 12, 658294.
- Karvar, M., Azari, A., Rahimi, A., Maddah-Hosseini, S., & Ahmadi-Lahijani, M. J. (2022). Titanium dioxide nanoparticles (TiO₂-NPs) enhance drought tolerance and grain yield of sweet corn (*Zea mays* L.) under deficit irrigation regimes. *Acta Physiologiae Plantarum*, 44(2), 14.
- Keskin, C., Ölçekçi, A., Baran, A., Baran, M. F., Eftekhari, A., Omarova, S., et al. (2023). Green synthesis of silver nanoparticles mediated *Diospyros kaki* L. (Persimmon): Determination of chemical composition and evaluation of their antimicrobials and anticancer activities. *Frontiers in Chemistry*, 11, 1187808.
- Khalid, A., Khan, R., Ul-Islam, M., Khan, T., & Wahid, F. (2017). Bacterial cellulose-zinc oxide nanocomposites as a novel dressing system for burn wounds. *Carbohydrate Polymers*, 164, 214–221.
- Khalil, N. M., Abd El-Ghany, M. N., & Rodríguez-Couto, S. (2019). Antifungal and antimycotoxin efficacy of biogenic silver nanoparticles produced by *Fusarium chlamydosporum* and *Penicillium chrysogenum* at non-cytotoxic doses. *Chemosphere*, 218, 477–486.
- Khan, S., Zahoor, M., Khan, R. S., Ikram, M., & Islam, N. U. (2023). The impact of silver nanoparticles on the growth of plants: The agriculture applications. *Heliyon*, 9(6), e16928.
- Kimber, R. L., Lewis, E. A., Parmeggiani, F., Smith, K., Bagshaw, H., Starborg, T., et al. (2018). Biosynthesis and characterization of copper nanoparticles using *Shewanella oneidensis*: Application for click chemistry. *Small*, 14(10), 1703145.
- Kopitke, P. M., Lombi, E., Wang, P., Schjoerring, J. K., & Husted, S. (2019). Nanomaterials as fertilizers for improving plant mineral nutrition and environmental outcomes. *Environmental Science: Nano*, 6(12), 3513–3524.
- Koul, B., Poonia, A. K., Yadav, D., & Jin, J.-O. (2021). Microbe-mediated biosynthesis of nanoparticles: Applications and future prospects. *Biomolecules*, 11(6), 886.
- Kowalczyk, B., Lagzi, I., & Grzybowski, B. A. (2011). Nanoseparations: Strategies for size and/or shape-selective purification of nanoparticles. *Current Opinion in Colloid & Interface Science*, 16(2), 135–148.
- Kumar, D., & Seth, C. S. (2021). Green-synthesis, characterization, and applications of nanoparticles (NPs): A mini review. *International Journal of Plant and Environment*, 7(01), 91–95.
- Kumar, A., Shah, S. R., Jayeoye, T. J., Kumar, A., Parihar, A., Prajapati, B., et al. (2023). Biogenic metallic nanoparticles: Biomedical, analytical, food preservation, and applications in other consumable products. *Frontiers in Nanotechnology*, 5, 1175149.
- Leonardi, M., Caruso, G. M., Carroccio, S. C., Boninelli, S., Curcuruto, G., Zimbone, M., et al. (2021). Smart nanocomposites of chitosan/alginate nanoparticles loaded with copper oxide as alternative nanofertilizers. *Environmental Science: Nano*, 8(1), 174–187.
- Li, J., Sang, H., Guo, H., Popko, J. T., He, L., White, J. C., et al. (2017). Antifungal mechanisms of ZnO and Ag nanoparticles to *Sclerotinia homoeocarpa*. *Nanotechnology*, 28(15), 155101.
- Li, M., Zhang, P., Adeel, M., Guo, Z., Chetwynd, A. J., Ma, C., et al. (2021). Physiological impacts of zero valent iron, Fe₃O₄ and Fe₂O₃ nanoparticles in rice plants and their potential as Fe fertilizers. *Environmental Pollution*, 269, 116134.
- Li, Q., Feng, T., Li, H., Wang, Z., Wei, X., & Liu, J. (2022a). Green synthesis of silver nanoparticles using endophytic bacterium *Bacillus zanthoxyli* GBE11 and their antimicrobial activity. *Biomass Conversion and Biorefinery*, 14, 13173–13185.

- Li, Q., Liu, F., Li, M., Chen, C., & Gadd, G. M. (2022b). Nanoparticle and nanomineral production by fungi. *Fungal Biology Reviews*, 41, 31–44.
- Lu, L., Zhuang, Z., Fan, M., Liu, B., Yang, Y., Huang, J., et al. (2022). Green formulation of Ag nanoparticles by *Hibiscus rosa-sinensis*: Introducing a novel chemotherapeutic drug for the treatment of liver cancer. *Arabian Journal of Chemistry*, 15(2), 103602.
- Mai, T., & Hilt, J. Z. (2017). Magnetic nanoparticles: Reactive oxygen species generation and potential therapeutic applications. *Journal of Nanoparticle Research*, 19, 1–10.
- Malhotra, A., Dolma, K., Kaur, N., Rathore, Y. S., Mayilraj, S., & Choudhury, A. R. (2013). Biosynthesis of gold and silver nanoparticles using a novel marine strain of *Stenotrophomonas*. *Bioresource Technology*, 142, 727–731.
- Malik, M. A., Wani, A. H., Bhat, M. Y., Siddiqui, S., Alamri, S. A., & Alrumman, S. A. (2024). Fungal-mediated synthesis of silver nanoparticles: A novel strategy for plant disease management. *Frontiers in Microbiology*, 15, 1399331.
- Mani, M., Pavithra, S., Mohanraj, K., Kumaresan, S., Alotaibi, S. S., Eraqi, M. M., et al. (2021). Studies on the spectrometric analysis of metallic silver nanoparticles (Ag NPs) using *Basella alba* leaf for the antibacterial activities. *Environmental Research*, 199, 111274.
- Manivasagan, P., Alam, M. S., Kang, K. H., Kwak, M., & Kim, S. K. (2015). Extracellular synthesis of gold bionanoparticles by *Nocardiopsis* sp. and evaluation of its antimicrobial, antioxidant and cytotoxic activities. *Bioprocess and Biosystems Engineering*, 38, 1167–1177.
- Manolescu, D., Uță, G. A., Șuțan, A., Ducu, C., Din, A., Moga, S., et al. (2022). Biogenic synthesis of noble metal nanoparticles using *Melissa officinalis* L. and *Salvia officinalis* L. extracts and evaluation of their biosafety potential. *Caryologia*, 75(3), 65–83.
- Maqsood, M. F., Shahbaz, M., Khalid, F., Rasheed, Y., Asif, K., Naz, N., et al. (2023). Biogenic nanoparticles application in agriculture for ROS mitigation and abiotic stress tolerance: A review. *Plant Stress*, 10, 100281. <https://doi.org/10.1016/j.stress.2023.100281>
- Metryka, O., Wasilkowski, D., Dulski, M., Adamczyk-Habrajska, M., Augustyniak, M., & Mrozik, A. (2024). Metallic nanoparticle actions on the outer layer structure and properties of *Bacillus cereus* and *Staphylococcus epidermidis*. *Chemosphere*, 354, 141691.
- Metuku, R. P., Pabba, S., Burra, S., Hima Bindu N, S. V. S. S. L., Gudikandula, K., & Singara Charya, M. A. (2014). Biosynthesis of silver nanoparticles from *Schizophyllum radiatum* HE 863742.1: their characterization and antimicrobial activity. *3 Biotech*, 4, 227–234.
- Michalak, I., & Chojnacka, K. (2015). Algae as production systems of bioactive compounds. *Engineering in Life Sciences*, 15(2), 160–176.
- Mikhailova, E. O. (2023). Selenium nanoparticles: Green synthesis and biomedical application. *Molecules (Basel, Switzerland)*, 28(24), 8125.
- Mishra, A., Kumari, M., Pandey, S., Chaudhry, V., Gupta, K. C., & Nautiyal, C. S. (2014). Biocatalytic and antimicrobial activities of gold nanoparticles synthesized by *Trichoderma* sp. *Bioresource Technology*, 166, 235–242.
- Moflikoane, L. B. (2015). *Enhancing the antifungal effect of antimicrobials against opportunistic and mycotoxigenic fungi using copper nanoparticles*. University of Johannesburg (South Africa).
- Momeni, S., & Nabipour, I. (2015). A simple green synthesis of palladium nanoparticles with *Sargassum* alga and their electrocatalytic activities towards hydrogen peroxide. *Applied Biochemistry and Biotechnology*, 176, 1937–1949.
- Monowar, T., Rahman, M. S., Bhore, S. J., & Sathasivam, K. V. (2021). Endophytic bacteria *Enterobacter hormaechei* fabricated silver nanoparticles and their antimicrobial activity. *Pharmaceutics*, 13(4), 511.
- More, P. R., Shinde, S., Cao, Z., Zhang, J., Pandit, S., De Filippis, A., et al. (2024). Antibacterial applications of biologically synthesized *Pichia pastoris* silver nanoparticles. *Heliyon*, 10(4), e25664.
- Niño-Martínez, N., Salas Orozco, M. F., Martínez-Castañón, G. A., Torres Méndez, F., & Ruiz, F. (2019). Molecular mechanisms of bacterial resistance to metal and metal oxide nanoparticles. *International Journal of Molecular Sciences*, 20(11), 2808.

- Otari, S., Patil, R., Nadaf, N., Ghosh, S., & Pawar, S. (2012). Green biosynthesis of silver nanoparticles from an actinobacteria *Rhodococcus* sp. *Materials Letters*, 72, 92–94.
- Pandimurugan, R., & Thambidurai, S. (2016). Novel seaweed capped ZnO nanoparticles for effective dye photodegradation and antibacterial activity. *Advanced Powder Technology*, 27(4), 1062–1072.
- Patra, J. K., Das, G., & Shin, H. S. (2019). Facile green biosynthesis of silver nanoparticles using *Pisum sativum* L. outer peel aqueous extract and its antidiabetic, cytotoxicity, antioxidant, and antibacterial activity. *International Journal of Nanomedicine*, 14, 6679–6690.
- Ponmurugan, P., Manjukarunambika, K., Elango, V., & Gnanamangai, B. M. (2016). Antifungal activity of biosynthesised copper nanoparticles evaluated against red root-rot disease in tea plants. *Journal of Experimental Nanoscience*, 11(13), 1019–1031.
- Prakash, V., Rai, P., Sharma, N. C., Singh, V. P., Tripathi, D. K., Sharma, S., & Sahi, S. (2022). Application of zinc oxide nanoparticles as fertilizer boosts growth in rice plant and alleviates chromium stress by regulating genes involved in oxidative stress. *Chemosphere*, 303, 134554.
- Prasad, K. S., Pathak, D., Patel, A., Dalwadi, P., Prasad, R., Patel, P., & Selvaraj, K. (2011). Biogenic synthesis of silver nanoparticles using nicotiana tobaccum leaf extract and study of their antibacterial effect. *African Journal of Biotechnology*, 10(41), 8122.
- Prema, P., Iniya, P. A., & Immanuel, G. (2016). Microbial mediated synthesis, characterization, antibacterial and synergistic effect of gold nanoparticles using *Klebsiella pneumoniae* (MTCC-4030). *RSC Advances*, 6(6), 4601–4607.
- Raj, L. F. A., & Jayalakshmy, E. (2015). Biosynthesis and characterization of zinc oxide nanoparticles using root extract of *Zingiber officinale*. *Oriental Journal of Chemistry*, 31(1), 51–56.
- Rajesh, K. M., Ajitha, B., Reddy, Y. A. K., Suneetha, Y., & Reddy, P. S. (2018). Assisted green synthesis of copper nanoparticles using *Syzygium aromaticum* bud extract: Physical, optical and antimicrobial properties. *Optik*, 154, 593–600.
- Rajeshkumar, S., Malarkodi, C., Gnanajobitha, G., Paulkumar, K., Vanaja, M., Kannan, C., & Annadurai, G. (2013). Seaweed-mediated synthesis of gold nanoparticles using *Turbinaria conoides* and its characterization. *Journal of Nanostructure in Chemistry*, 3, 1–7.
- Rajivgandhi, G., Mythili Gnanamangai, B., Heela Prabha, T., Poornima, S., Maruthupandy, M., Alharbi, N. S., et al. (2022). Biosynthesized zinc oxide nanoparticles (ZnO NPs) using actinomycetes enhance the anti-bacterial efficacy against *K. Pneumoniae*. *Journal of King Saud University – Science*, 34(1), 101731.
- Rajput, S., Werezuk, R., Lange, R. M., & McDermott, M. T. (2016). Fungal isolate optimized for biogenesis of silver nanoparticles with enhanced colloidal stability. *Langmuir*, 32(34), 8688–8697.
- Ramadan, K. M., & El-Beltagi, H. S. (2021). Biosynthesis of nanoparticles by microorganisms and applications in plant stress control. In *Plant growth-promoting microbes for sustainable biotic and abiotic stress management* (pp. 319–353). Springer.
- Ramanathan, R., O'Mullane, A. P., Parikh, R. Y., Smooker, P. M., Bhargava, S. K., & Bansal, V. (2011). Bacterial kinetics-controlled shape-directed biosynthesis of silver nanoplates using *Morganella psychrotolerans*. *Langmuir*, 27(2), 714–719.
- Ramesh, P. S., Kokila, T., & Geetha, D. (2015). Plant mediated green synthesis and antibacterial activity of silver nanoparticles using *Emblca officinalis* fruit extract. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 142, 339–343.
- Ranjitha, V. R., & Rai, V. R. (2017). Actinomycetes mediated synthesis of gold nanoparticles from the culture supernatant of *Streptomyces griseoruber* with special reference to catalytic activity. *3 Biotech*, 7, 1–7.
- Raut, R. W., Haroon, A. S. M., Malghe, Y. S., Nikam, B. T., & Kashid, S. B. (2013). Rapid biosynthesis of platinum and palladium metal nanoparticles using root extract of *Asparagus racemosus* Linn. *Advanced Materials Letters*, 4(8), 650–654.

- Rezaei, M., & Abbasi, H. (2014). Foliar application of nanochelate and non-nanochelate of zinc on plant resistance physiological processes in cotton (*Gossipium hirsutum* L.). *Iranian Journal of Plant Physiology*, 4(4), 1137–1144.
- Rizzo, D. M., Lichtveld, M., Mazet, J. A., Togami, E., & Miller, S. A. (2021). Plant health and its effects on food safety and security in a one health framework: Four case studies. *One Health Outlook*, 3(1), 6.
- Roychoudhury, A. (2020). Yeast-mediated green synthesis of nanoparticles for biological applications. *Indian Journal of Pharmaceutical and Biological Research*, 8(03), 26–31.
- Rui, M., Ma, C., Hao, Y., Guo, J., Rui, Y., Tang, X., et al. (2016). Iron oxide nanoparticles as a potential iron fertilizer for peanut (*Arachis hypogaea*). *Frontiers in Plant Science*, 7, 815.
- Saad, E., Salem, S. S., Fouda, A., Awad, M. A., El-Gamal, M. S., & Abdo, A. M. (2018). New approach for antimicrobial activity and bio-control of various pathogens by biosynthesized copper nanoparticles using endophytic actinomycetes. *Journal of Radiation Research and Applied Sciences*, 11(3), 262–270.
- Saeed, S., Iqbal, A., & Ashraf, M. A. (2020). Bacterial-mediated synthesis of silver nanoparticles and their significant effect against pathogens. *Environmental Science and Pollution Research*, 27(30), 37347–37356.
- Saha, R., Subramani, K., Sikdar, S., Fatma, K., & Rangaraj, S. (2021). Effects of processing parameters on green synthesised ZnO nanoparticles using stem extract of *Swertia chirayita*. *Biocatalysis and Agricultural Biotechnology*, 33, 101968.
- Saheb, M., Hosseini, H. A., Hashemzadeh, A., Elahi, B., Hasanzadeh, L., Oskuee, R. K., & Darroudi, M. (2019). Photocatalytic and biological attributes of green synthesized nickel oxide nanoparticles by *Rheum turkestanicum* (RT) root extract. *ChemistrySelect*, 4(8), 2416–2420.
- Sahoo, B., Rath, S. K., Mahanta, S. K., & Arakha, M. (2021). Nanotechnology mediated detection and control of phytopathogens. In *Bio-nano interface: Applications in food, healthcare and sustainability* (pp. 109–125). Springer Singapore.
- Salari, S., Esmailzadeh Bahabadi, S., Samzadeh-Kermani, A., & Yosefzaei, F. (2019). In-vitro evaluation of antioxidant and antibacterial potential of GreenSynthesized silver nanoparticles using *Prosopis farcta* fruit extract. *Iranian Journal of Pharmaceutical Research: IJPR*, 18(1), 430–455.
- Salem, S. S., & Fouda, A. (2021). Green synthesis of metallic nanoparticles and their prospective biotechnological applications: An overview. *Biological Trace Element Research*, 199(1), 344–370.
- Satpathy, S., Panigrahi, L. L., Samal, P., Sahoo, K. K., & Arakha, M. (2024). Biogenic synthesis of selenium nanoparticles from *Nyctanthes arbor-tristis* L. and evaluation of their antimicrobial, antioxidant and photocatalytic efficacy. *Heliyon*, 10(12), e32499.
- Senapati, S., Syed, A., Moez, S., Kumar, A., & Ahmad, A. (2012). Intracellular synthesis of gold nanoparticles using alga *Tetraselmis kochinensis*. *Materials Letters*, 79, 116–118.
- Shamim, A., Mahmood, T., & Abid, M. B. (2019). Biogenic synthesis of zinc oxide (ZnO) nanoparticles using a fungus (*Aspergillus Niger*) and their characterization. *International Journal of Chemistry*, 11(2), 119.
- Sharma, R., Sharma, R., Singh, R. R., & Kumari, A. (2023). Evaluation of biogenic zinc oxide nanoparticles from *Tinospora cordifolia* stem extract for photocatalytic, anti-microbial, and antifungal activities. *Materials Chemistry and Physics*, 297, 127382.
- Shende, S. S., Ingle, P. U., Rajput, V. D., Gade, A. K., Minkina, T. M., Sushkova, S. N., et al. (2021). Biogenic synthesis of silver and gold nanoparticles by microbes. In *Microbial synthesis of nanomaterials* (pp. 47–78). Nova Science Publishers USA.
- Singh, B. R., Dwivedi, S., Al-Khedhairi, A. A., & Musarrat, J. (2011). Synthesis of stable cadmium sulfide nanoparticles using surfactin produced by *Bacillus amyloliquefaciens* strain KSU-109. *Colloids and Surfaces B: Biointerfaces*, 85(2), 207–213.

- Singh, M., Kalaivani, R., Manikandan, S., Sangeetha, N., & Kumaraguru, A. K. (2013). Facile green synthesis of variable metallic gold nanoparticle using *Padina gymnospora*, a brown marine macroalga. *Applied Nanoscience*, 3, 145–151.
- Singh, P., Kim, Y. J., Wang, C., Mathiyalagan, R., & Yang, D. C. (2016). The development of a green approach for the biosynthesis of silver and gold nanoparticles by using *Panax ginseng* root extract, and their biological applications. *Artificial Cells, Nanomedicine, and Biotechnology*, 44(4), 1150–1157.
- Skalikova, S., Baron, M., & Sochor, J. (2017). Nanoparticles biosynthesized by yeast: A review of their application. *Kvasny Prumysl*, 63(6), 290–292.
- Soliman, M. I., Mohammed, N. S., El-Sherbeny, G., Safhi, F. A., ALshamrani, S. M., Alyamani, A. A., et al. (2022). Antibacterial, antioxidant activities, GC-mass characterization, and cyto/genotoxicity effect of green synthesis of silver nanoparticles using latex of *Cynanchum acutum* L. *Plants*, 12(1), 172.
- Song, J. Y., Kwon, E. Y., & Kim, B. S. (2010). Biological synthesis of platinum nanoparticles using *Diopyros kaki* leaf extract. *Bioprocess and Biosystems Engineering*, 33, 159–164.
- Sujitha, M. V., & Kannan, S. (2013). Green synthesis of gold nanoparticles using Citrus fruits (*Citrus Limon*, *Citrus reticulata* and *Citrus sinensis*) aqueous extract and its characterization. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 102, 15–23.
- Sun, Q., Li, J., & Le, T. (2018). Zinc oxide nanoparticle as a novel class of antifungal agents: Current advances and future perspectives. *Journal of Agricultural and Food Chemistry*, 66(43), 11209–11220.
- Sundrarajan, M., & Muthulakshmi, V. (2021). Green synthesis of ionic liquid mediated neodymium oxide nanoparticles by *Andrographis paniculata* leaves extract for effective bio-medical applications. *Journal of Environmental Chemical Engineering*, 9(1), 104716.
- Taghizadeh, S. M., Lal, N., Ebrahiminezhad, A., Moeini, F., Seifan, M., Ghasemi, Y., & Berenjian, A. (2020). Green and economic fabrication of zinc oxide (ZnO) nanorods as a broadband UV blocker and antimicrobial agent. *Nanomaterials*, 10(3), 530.
- Tahir, K., Nazir, S., Li, B., Khan, A. U., Khan, Z. U. H., Ahmad, A., & Khan, F. U. (2015). An efficient photo catalytic activity of green synthesized silver nanoparticles using *Salvadora persica* stem extract. *Separation and Purification Technology*, 150, 316–324.
- Taleblian, S., Shahnavaz, B., Nejabat, M., Abolhassani, Y., & Rassouli, F. B. (2023). Bacterial-mediated synthesis and characterization of copper oxide nanoparticles with antibacterial, antioxidant, and anticancer potentials. *Frontiers in Bioengineering and Biotechnology*, 11, 1140010.
- Thatyana, M., Dube, N. P., Kemboi, D., Manicum, A. L. E., Mokgalaka-Fleischmann, N. S., & Tembu, J. V. (2023). Advances in phytonanotechnology: A plant-mediated green synthesis of metal nanoparticles using *phyllanthus* plant extracts and their antimicrobial and anticancer applications. *Nanomaterials*, 13(19), 2616.
- Torabfam, M., & Yüce, M. (2020). Microwave-assisted green synthesis of silver nanoparticles using dried extracts of *Chlorella vulgaris* and antibacterial activity studies. *Green Processing and Synthesis*, 9(1), 283–293.
- Tripathi, R., Bhadwal, A. S., Gupta, R. K., Singh, P., Shrivastav, A., & Shrivastav, B. (2014). ZnO nanoflowers: Novel biogenic synthesis and enhanced photocatalytic activity. *Journal of Photochemistry and Photobiology B: Biology*, 141, 288–295.
- Tripathi, R. M., Shrivastav, B. R., & Shrivastav, A. (2018). Antibacterial and catalytic activity of biogenic gold nanoparticles synthesised by *Trichoderma harzianum*. *IET Nanobiotechnology*, 12(4), 509–513.
- Tudi, M., Daniel Ruan, H., Wang, L., Lyu, J., Sadler, R., Connell, D., et al. (2021). Agriculture development, pesticide application and its impact on the environment. *International Journal of Environmental Research and Public Health*, 18(3), 1112.
- Tyavambiza, C., Elbagory, A. M., Madiehe, A. M., Meyer, M., & Meyer, S. (2021). The antimicrobial and anti-inflammatory effects of silver nanoparticles synthesised from *Cotyledon orbiculata* aqueous extract. *Nanomaterials*, 11(5), 1343.
- Vanaja, M., Rajeshkumar, S., Paulkumar, K., Gnanajobitha, G., Malarkodi, C., & Annadurai, G. (2013). Phytosynthesis and characterization of silver nanoparticles using stem extract of

- Coleus aromaticus*. *International Journal of Materials and Biomaterials Applications*, 3(1), 1–4.
- Velmurugan, P., Anbalagan, K., Manosathyadevan, M., Lee, K. J., Cho, M., Lee, S. M., et al. (2014). Green synthesis of silver and gold nanoparticles using *Zingiber officinale* root extract and antibacterial activity of silver nanoparticles against food pathogens. *Bioprocess and Biosystems Engineering*, 37, 1935–1943.
- Venkateswarlu, S., Kumar, B. N., Prathima, B., Anitha, K., & Jyothi, N. V. V. (2015). A novel green synthesis of Fe₃O₄-Ag core shell recyclable nanoparticles using *Vitis vinifera* stem extract and its enhanced antibacterial performance. *Physica B: Condensed Matter*, 457, 30–35.
- Verma, K. K., Song, X. P., Joshi, A., Tian, D. D., Rajput, V. D., Singh, M., et al. (2022). Recent trends in nano-fertilizers for sustainable agriculture under climate change for global food security. *Nanomaterials*, 2022(12), 173.
- Waghmare, S. R., Mulla, M. N., Marathe, S. R., & Sonawane, K. D. (2015). Ecofriendly production of silver nanoparticles using *Candida utilis* and its mechanistic action against pathogenic microorganisms. *3 Biotech*, 5, 33–38.
- Wang, P., Lombi, E., Zhao, F. J., & Kopittke, P. M. (2016). Nanotechnology: A new opportunity in plant sciences. *Trends in Plant Science*, 21(8), 699–712.
- Wang, Y., Lin, Y., Xu, Y., Yin, Y., Guo, H., & Du, W. (2019). Divergence in response of lettuce (var. *ramosa* Hort.) to copper oxide nanoparticles/microparticles as potential agricultural fertilizer. *Environmental Pollutants and Bioavailability*, 31(1), 80–84.
- Yousaf, N., Ishfaq, M., Qureshi, H. A., Saleem, A., Yang, H., Sardar, M. F., & Zou, C. (2023). Characterization of root and foliar-applied iron oxide nanoparticles (α -Fe₂O₃, γ -Fe₂O₃, Fe₃O₄, and bulk Fe₃O₄) in improving maize (*Zea mays* L.) performance. *Nanomaterials*, 13(23), 3036.
- Youssef, K., Hashim, A. F., Hussien, A., & Abd-Elsalam, K. A. (2017). Fungi as ecosynthesizers for nanoparticles and their application in agriculture. In *Fungal nanotechnology: applications in agriculture, industry, and medicine* (pp. 55–75).
- Yugandhar, P., Vasavi, T., Jayavardhana Rao, Y., Uma Maheswari Devi, P., Narasimha, G., & Savithramma, N. (2018). Cost effective, green synthesis of copper oxide nanoparticles using fruit extract of *Syzygium alternifolium* (Wt.) Walp., characterization and evaluation of antiviral activity. *Journal of Cluster Science*, 29, 743–755.
- Zafar, S., Ashraf, M. Y., & Saleem, M. (2018). Shift in physiological and biochemical processes in wheat supplied with zinc and potassium under saline condition. *Journal of Plant Nutrition*, 41(1), 19–28.
- Zhang, X., Qu, Y., Shen, W., Wang, J., Li, H., Zhang, Z., et al. (2016). Biogenic synthesis of gold nanoparticles by yeast *Magnusiomyces ingens* LH-F1 for catalytic reduction of nitrophenols. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 497, 280–285.
- Zhang, D., Ma, X. L., Gu, Y., Huang, H., & Zhang, G. W. (2020). RETRACTED: Green synthesis of metallic nanoparticles and their potential applications to treat cancer. *Frontiers in Chemistry*, 8, 799.

Chapter 9

Biogenic Synthesis of Copper-Based Nanoparticles and Their Applications in Plant Protection



Tarek H. M. Elsharouny

Abstract The use of plants and microorganisms as biological synthesizers of nanoparticles is considered the future of modern agriculture, as chemical nanosynthesis and excessive use of fertilizers and pesticides to improve plant growth and control plant diseases and insects have had very negative effects on the environment. This chapter investigates the forms of copper nanoparticles (CuNPs) that have been used recently in plant protection, listed the growing importance of these particles in this area. It has been clarified that copper oxide nanoparticles are considered one of the most widely used forms in the field of agriculture, followed in importance by copper sulphate. The availability of many plants that can be used in the biosynthesis of copper nanoparticles makes the green synthesis of nanoparticles cheaper and easier than other biological methods. This chapter demonstrated how easy it is to synthesize nanoparticles using plant extracts. Other biological methods for synthesizing copper nanoparticles using microorganisms such as bacteria, fungi, viruses and algae were discussed. Characterization methods such as UV-Vis spectroscopy, transmission electron microscopy (TEM), scanning electron microscope (SEM), atomic force microscopy (AFM), Fourier transform infrared spectroscopy (FTIR), atomic absorption spectroscopy (AAS), energy dispersive spectroscopy (EDS), surface enhanced residual spectroscopy (SERS), beam photoelectron spectroscopy (XPS), X-ray diffraction (XRD), high-angle annular dark field (HAADF), dynamic light scattering (DLS) and zeta potential are demonstrated in detail. Finally, the application of copper nanoparticles in plant protection as a pesticide, bactericide, and fungicide was demonstrated and showed that the use of biologically synthesized copper nanoparticles was very effective against plant pests and pathogens.

Keywords Biosynthesis · Copper nanoparticles · Characterization · Applications

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9.1 Introduction

In developing nations, agriculture is one of the main pillars of the national economy. An increase in a nation's Gross Domestic Product (GDP) is largely dependent on rising rates of food production. The nation's use of pesticides and fertilizers affects the pace at which food is produced. A number of factors directly affect food production and the expansion of agriculture, including water availability, soil health, climate change, and food security. As a result, it's essential to control the unfavorable agricultural conditions in order to increase food production in a way that will support the growing global population (Chhipa, 2019).

Through applications in the fields of food and agriculture, such as enhanced food quality and safety, decreased agricultural inputs, and enhanced nanoscale nutrient absorption from the soil, biosynthesized nanoparticles offer enormous potential for improving the quality of life through green technology. Growth potential is found in agriculture, smart agrochemical delivery systems (e.g., fertilizers, pesticides), early food material disease detection, system integration for food processing, packaging, monitoring, and natural reservoir management (Devra, 2022).

Although there are several ways to create nanoparticles, chemical processes are the most common way. However, certain chemical processes cannot avoid the use of toxic substances during the synthesis process. Since metal nanoparticles are widely applied to human contacting areas, there is an increasing need to create ecologically safe methods of synthesizing nanoparticles that don't include harmful chemicals. Environmentally acceptable alternatives for chemical and physical processes in the creation of nanoparticles have been proposed: biological methods using microbes, enzymes, plants, or plant extract (Lee et al., 2011). Copper is a vital micronutrient that is crucial to the well-being of every living thing. It is integrated into a variety of proteins and metalloenzymes that are necessary for the cells and organisms of plants to carry out different metabolic processes (Kasana et al., 2016).

Applications of copper nanoparticles (Cu-NPs) in agriculture for disease and pest control are looking very promising. For effective pesticide and fertilizer delivery and controlled release, copper-based nanoparticles like Cu-NPs and CuO-NPs are being utilized more and more in nanoformulations and agrochemicals. Additional uses in agriculture include antifungal and antibacterial properties, plant protection, plant growth promotion, and nanosensors (Kasana et al., 2017).

CuNPs as antibacterial substances. As per reports from the Environment Protection Agency (EPA), copper has been recognized as a potent antimicrobial agent that can effectively reduce approximately 99.99% of the microbial concentration that causes fatal diseases (Leong et al., 2023). Because of their small size, copper nanoparticles are inexpensive to use in agriculture and are easily absorbed by plants. It has demonstrated its antagonistic effects against insects, fungi, crop plant pests, etc. With multiple cost advantages, it may thus be investigated as nanopesticides, nanoherbicides, and nanofertilizers. The additional expense associated with using fungicides, pesticides, and fertilizers separately in conventional agriculture is eliminated by using copper nanoparticles (CuNPs) alone as a fungicide, pesticide, micronutrient, and fertilizer (Bhagat et al., 2021).

This chapter describes methods of biosynthesis and characterization of copper nanoparticles and their application in plant protection.

9.2 Forms of Copper Nanoparticles

Numerous copper-containing nanoparticles (NPs) have been effectively synthesized, including copper NPs (Cu-NPs), copper oxide NPs (CuO-NPs), and copper-containing bimetallic NPs (Erci et al., 2020; Arakawa et al., 2020). Copper oxide nanoparticles have attracted great interest for several decades due to their unique properties (Verma & Kumar, 2019). These nanoparticles can be used in many different fields, including textiles, gas sensors, batteries and catalysis. Nevertheless, copper oxide nanoparticles are toxic when produced by physical and chemical means (Khatoon et al., 2018).

Therefore, researchers chose an environmentally friendly synthesis method to address the toxicity problem. The green route includes a wide range of bioactive compounds, and green synthesized copper oxide nanoparticles are biocompatible, stable, safe, economical and environmentally friendly (Akintelu et al., 2020). Using a variety of extracts, copper oxide nanoparticles are biogenically produced and used in biomedical devices as coating agents, antifungal, antibacterial, and antibiofilm agents. To prevent microbial damage as well as discoloration, corrosion, contamination and a reduction in mechanical strength, textiles with antimicrobial potential are manufactured (Husen & Iqbal, 2019; Jadoun et al. 2021a, b). As antimicrobial agents, copper oxide (Cu₂O) and copper oxide (CuO) are frequently employed. The advantages of copper oxide over organic antimicrobial agents include strength, stability in both physical and chemical properties and a comparatively long shelf life. Furthermore, the physical characteristics of copper oxide facilitate its easy mixing with polymers, enabling the processing of CuO NPs into a range of composite materials. Cu NPs are more oxidatively unstable and less stable than CuO NPs. Because copper (Cu) easily oxidizes to Cu₂O and CuO in the presence of air, synthesizing Cu NPs in an ambient setting is challenging. As a result, coatings must typically be formed on the surface of Cu NPs and they must be synthesized in the presence of polymers and surfactants (Ma et al., 2022).

Copper sulfide (CuS) nanoparticles are emerging as a versatile tool in biomedical research due to their unique properties and potential for diverse applications. Traditionally studied for energy storage and catalysis, CuS NPs are now being recognized for their relevance in biomedicine, where their eco-friendly, cost-effective, and simple production methods make them attractive.

These NPs exhibit impressive spectroscopic properties, allowing for applications in imaging, diagnostics, and therapeutic techniques. Their high biocompatibility and electrochemical performance open doors to biosensing and drug delivery applications, where these properties facilitate controlled interaction with biological systems. The combination of these features positions CuS NPs as a promising material in

biotechnological and medical research, paving the way for innovative diagnostics, treatment options, and biotechnological solutions (Saona et al., 2022; ul Ain et al., 2022).

9.3 Biological Methods of Synthesizing Copper Nanoparticles

The need for creating high-yield, affordable, non-toxic, and ecologically friendly processes to create metallic nanoparticles is growing. It is therefore crucial to use a biological method when creating nanoparticles. In order to create nanoparticles, a wide range of biological resources found in nature could be employed, such as bacteria, viruses, algae, fungi, yeasts, and plants and their products. Inorganic materials are produced either intracellularly or extracellularly by both unicellular and multicellular organisms, as is well known (Thakkar et al., 2010).

There are two types of traditional methods for NP synthesis: top-down and bottom-up methods, as shown in Fig. 9.1 of Rawat (2015). These categories differ mainly in how they proceed. What differs most is the raw material used to create NPs. Top-down approaches use a variety of physical, chemical and mechanical techniques, including sputtering, mechanical milling and laser ablation, to break down the bulk material into nanoparticles. Atoms or molecules are used as starting material for the formation of NPs in bottom-up methods such as vapor deposition, chemical reduction, spray pyrolysis, and biological/green synthesis (Antonio-Pérez et al., 2023).

9.3.1 Synthesis of Cu Nanoparticles by Plants

CuNPs produced biologically from plant extracts are highly desired after for their many industrial applications and uses because of their unique and adjustable characteristics, including high surface area, superior conductivity, stability, oxidation, and chemical reactivity (Luque-Jacobo et al., 2023).

Fig. 9.1 “Top-down” and “bottom-up” synthesis of nanoparticles (Rawat, 2015)

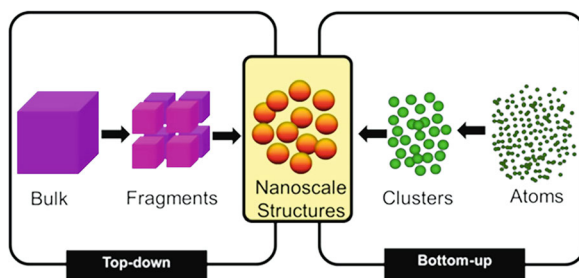


Table 9.1 Plants that used to synthesize copper nanoparticles (Shobha et al., 2014)

No.	Angiospermic plant	Parts used	Particle size
1	<i>Calotropis procera L.</i>	Latex	15 ± 1.7 nm.
2	<i>Euphorbia nivulia</i>	Latex	–
3	<i>Gum karaya</i>	Gum	4.8 ± 1.6 nm
4	<i>Helianthus annus</i>	–	–
5	<i>Lantana camara</i>	–	Average of 20 nm
6	<i>Magnolia</i>	Leaves	40–100 nm
7	<i>Magnolia kobus</i>	Leaves	Average size 37–110 nm
8	<i>Medicago sativa</i>	–	–
9	<i>Ocimum sanctum</i>	Leaves	77 nm
10	<i>Soy beans</i>	Seed	–
11	<i>Syzygium aromaticum</i>	Flower buds	40–45 nm
12	<i>Tridax procumbens</i>	–	–
13	<i>Zingiber officinale</i>	Rhizome	40 and 25 nm

As reducing, stabilizing, and capping agents, biological syntheses utilizing naturally occurring plant extracts, such as those from leaves, fruits, stems, roots, flowers, and seeds, or plant-produced materials, like latex, have been employed. The metal salt interacts with the organic compounds in the extract—such as proteins, amino acids, organic acids, vitamins, and secondary metabolites, or bioactive compounds—like flavonoids, alkaloids, polyphenols, terpenoids, heterocyclic compounds, etc.—to produce nanoparticles. Binding agent-producing polysaccharides may have an impact. Furthermore, without the addition of artificial polymers and surfactants, these organic compounds can aid in the control and formation of homogeneous shapes, such as spherical, linear, and cubic shapes with an average size of 10–100 nm (Patel et al., 2016). Thus, compared to the synthesis of microorganisms, plant extracts might be a more affordable way to create nanoparticles (Luque-Jacobo et al., 2023).

Over 60 Plant-mediated synthesis of copper oxide nanoparticles were stated by Waris et al. (2021). Several plants were found to synthesize copper nanoparticles, as stated in Table 9.1 (Shobha et al., 2014).

9.3.1.1 Extraction of Plant Produced Metal Nanoparticles

As shown in Fig. 9.2, plant parts can be thoroughly cleaned with tap water, sterilized with double-distilled water, and then allowed to dry at room temperature in order to create nanoparticles from their flowers and leaves. Weighing and crushing the dried sample are done. After that, the plant extract is combined with Milli-Q H₂O to the appropriate concentration and boiled while being constantly stirred. After using Whatman filter paper to filter the resultant solution, the portion that contains a clear solution can be used as a sample (plant extract) (Jadoun et al., 2021a, b).

during biosynthesis. It's crucial to understand the origin and mechanism of this biosynthesis because using toxic microorganisms as bioresources could introduce pathogenicity to the synthesized MtNPs. Additionally, while lab-scale protocols can produce well-characterized and highly stable metallic nanoparticles, scaling up to an industrial level is necessary to address unmet medical needs. This requires optimizing microbial growth rates, inoculating the seed into biomass, harvesting cells, and ensuring effective MtNP preparation through reduction, as well as efficiently recovering the final product with a good yield (Korbekandi et al., 2012).

Microbial synthesis of nanoparticles (NPs) is a bottom-up approach (Fig. 9.1) that utilizes simple unicellular to more complex multicellular organisms, such as bacteria, fungi, actinomycetes, and yeast. This brings us to discuss the mechanisms involved in the microbial synthesis of nanoparticles.

9.3.2.1 Mechanism of Synthesizing Nanoparticles Using Microorganisms

Microbes utilize various mechanisms for the synthesis of NPs, including changes in solubility, biosorption, metal complexation, extracellular precipitation, toxicity via oxidation-reduction, the absence of specific transporters and efflux pumps.

Lahiri et al. (2021) reported that both intracellular and extracellular nanoparticle (NP) synthesis by microorganisms from metals, metal oxides, or metalloids has been thoroughly studied (Patil and Chandrasekaran, 2020). In the extracellular process, microbial enzymes, proteins, cell wall components, or organic molecules in the culture medium reduce metal ions to synthesize NPs. In the intracellular process, metal ions are first attracted by the carboxyl groups on the microbial cell wall, allowing them to enter the cell, where they are reduced by intracellular proteins and cofactors to form NPs (Siddiqi et al., 2018). These biochemical mechanisms of microorganism-mediated NP synthesis can be understood as part of the microbial resistance system for detoxifying cells.

Microbial resistance strategies for cellular detoxification may include biochemical processes including the creation of nanoparticles mediated by microorganisms. This process involves changing the solubility of inorganic and toxic ions through enzymatic reduction and/or precipitation into nanostructures. Both extracellular and intracellular bio-catalytic synthesis mechanisms have been suggested, primarily involving oxidoreductase enzymes, such as NADH-dependent nitrate reductase, NADPH-dependent sulfite reductase flavoprotein subunit α , and cysteine decahydrate, as well as cellular transporters (Grasso et al., 2019).

Through the use of cellular enzymes, microorganisms biosynthesize nanomaterials by absorbing target ions from their surroundings and converting them into their elemental form. Depending on where the nanoparticles are synthesized, the process can be classified as either intracellular or extracellular. In the intracellular method, ions are transported into the microbial cell, where nanoparticles are formed with the help of enzymes. In the extracellular method, metal ions are trapped on the cell surface and reduced in the presence of enzymes (Li et al., 2011).

9.4 Bacterial Synthesis of Copper Nanoparticles

For the synthesis of metallic nanoparticles in natural resource environments, prokaryotic bacteria have been the subject of the most research. Because they are relatively easy to handle, bacteria have a “preference” for creating nanoparticles (Thakkar et al., 2010).

Recently, a number of nanoparticles, including copper nanoparticles, have been produced using bacteria (Narayanan & Sakthivel, 2010). Through intracellular or extracellular means, bacteria have been used to produce a variety of materials with intriguing shapes and nanoscale dimensions. The ability to produce nanoparticles from bacteria is promising. The advantages they offer include short generation time, easy culture, favorable experimental conditions, excellent stability, synthesis of extracellular nanoparticles, and easy genetic modification (Jadoun et al., 2021a, b). It is known that microorganisms learn to survive in an environment with hazardous metals by converting the toxic metal ions into non-toxic forms such as metal sulfides or oxides. It is well known that bacteria can survive in environments with high concentrations of hazardous metals by converting toxic metal ions into nontoxic metal oxides (Saif Hasan et al., 2008). It has been shown that bacteria can produce a variety of important thiol-containing compounds in response to oxidative stress. These molecules are a protective agent that prevents the oxidation of metal oxide nanoparticles during the bacterially induced nanoparticle production process (Araújo et al., 2018).

Different types of bacteria were employed to synthesize copper oxide nanoparticles such as *Serratia* sp. (Saif Hasan et al., 2008) and *Pseudomonas stutzeri* (Varshney et al., 2010). *Lactobacillus casei* (Kouhkan et al., 2020), *Mycobacterium psychrotolerans* (Ramanathan et al., 2013), *Pseudomonas fluorescens* (Shantkriti & Rani, 2014) *E. coli* (Ghorbani et al., 2015), *Bacillus cereus* (Tiwari et al., 2016), *Shewanella oneidensis* MR-1 (Zhou et al., 2016) were used to synthesize copper sulfide nanoparticles (CuS-NPs) extracellularly. Endophytic actinomycete (Hassan et al., 2019), *Streptomyces* sp. MHM3 (Bukhari et al., 2021), *Morganella* sp. (Chakraborty et al., 2022), and the bacteria *Aeromonas hydrophila* (Rajeshkumar et al., 2022) all found that they synthesized copper oxide nanoparticles. Mohamed et al. (2023) reported that the bacteria *Streptomyces thermolilacinus* was used in the synthesization of copper oxide nanoparticles. Kashyap et al. (2023) confirmed that the *Stenotrophomonas maltophilia* SCS1.1 strain performs the extracellular synthesis of copper NPs through the reduction of copper sulfate ions. Batool et al. (2024) demonstrated the bacterial synthesis of Cu-NPs using a *Bacillus flexus* strain isolated from textile wastewater.

9.5 Mycosynthesis of Copper Nanoparticles

Because of their tolerance and metal bioaccumulation ability, fungi are taking the center stage of studies on the biological generation of metallic nanoparticles. Since the rational synthesis of nanoparticles using fungi offers several advantages over

bacteria, Fungi can produce nanoparticles with more consistent nanoscale dimensions and improved monodispersity compared to those synthesized by bacteria. Additionally, fungi possess effective strategies for extracellular nanoparticle synthesis, which enhances their commercial viability (Das et al., 2017).

Fungi are also attractive hosts for inorganic NM biosynthesis owing to their high tolerance to metal and non-metal ions. Fungi generally express large amounts of enzymes, non-enzymatic proteins and peptides for the biosynthesis of inorganic NMs. Some disadvantages of using fungi are their slower growth and difficulties in genetic manipulation compared with bacteria (Choi & Lee, 2020).

Fungal endophytes are mainly symbionts of plants that not only help the survival of the plant but also have significant potential in the field of natural products and act as small factories producing metal nanoparticle (Mostafazade et al., 2024).

Furthermore, Fungi are excellent sources of secondary metabolites and active biomolecules, which serve as stabilizing and reducing agents in nanoparticle (NP) synthesis. Furthermore, functional groups like $\text{C}=\text{C}$ -, $\text{C}-\text{O}-\text{R}$, $\text{C}-\text{O}-\text{C}$, and $\text{C}=\text{O}$, derived from fungal proteins, act as capping ligands to stabilize the Cu nanoparticles (Nthunya et al., 2023).

Narayanan and Sakthivel (2010) reported that fungal-mediated production of CuNPs utilizes two pathways: (1) intracellular and extracellular. The intracellularly produced CuNPs from fungal species exhibit good dispersion and uniformity in terms of particle size, shape and texture. Meanwhile, (2) the extracellular pathway, which produces larger and purer NPs.

Fusarium oxysporum was used to synthesize copper sulfide nanoparticles in an inexpensive and sustainable approach (Hosseini et al., 2012). *Aspergillus niger* was utilized for the synthesis of copper nanoparticles (CuNPs), which were subsequently characterized by Noor et al. (2020) and Sahithya et al. (2024). Various species of fungi such as *Penicillium aurantiogriseum* and *Penicillium citrinum* (Honary et al., 2012), *Hypocrea lixii* (Salvadori et al., 2013), *Stereum hirsutum* (Cuevas et al., 2015), *Shewanella loihica* (Lv et al., 2018), *Pleurotus ostreatus* (El-Batal et al., 2018), *Trichoderma asperellum* (Saravanakumar et al., 2019) *Aspergillus terreus* (Nassar et al., 2023), *Trichoderma virens* and *Chaetomium globosum* (Dorjee et al., 2024), *Phoma glomerata* (Ingle et al., 2024), and *Aspergillus carbonarius* (Al-Qaissi et al., 2024) have been evaluated for the synthesis of CuNPs.

9.6 Biosynthesis of Copper Nanoparticles by Viruses

viruses have an important characteristic of such thick capsid protein outer surface coating, which offers a very appropriate platform for interaction with metallic ions (Kobayashi et al., 2012).

Zeng et al. (2013) showed that through genetic engineering, these protein cages can create very durable, moldable monodisperse units. Viruses can be altered to act as templates for the deposition of materials or designed to produce three-dimensional vessels for the delivery of targeted pharmaceuticals.

The advantages of using viruses for metal nanoparticle biosynthesis include the fact that they are extremely diverse organisms found everywhere, environmentally friendly methods, unique enzymes and structures that increase synthesis efficiency, and unique selectivity because viruses are specific bound to bacteria, which improves the accuracy of the biosynthesis process. Since bacteriophage proteins or peptides serve as appropriate capping, reducing and stabilizing components in the formation of nanoparticles, they are used as natural agents in the formation of metal nanoparticles.

However, the use of viruses in nanoparticle synthesis has disadvantages, such as the employ of viruses may form limitations in the shape and size of nanoparticles, the complexity of the manufacturing process, need special conditions, and limitations in the choice of metals, which in some viruses only biosynthesize a specific metal. The few disadvantages, including biosynthesis of nanoparticles by bacteriophage, are the long synthesis time and loss of purification nanoparticles stage, and they can interact with the immune system and induce harmful immune responses, which is a concern for clinical applications of bacteriophage-mediated nanoparticle synthesis (Ahiwale et al., 2017; Paczesny & Bielec, 2020; Ogunyemi et al., 2023).

Various investigations have demonstrated that different phages, such as C3, ZC5S1, P1, ϕ 6, and M13, have been applied for the biosynthesis of various nanoparticles. Such Phage M13 has shown the ability for the formation nanoparticles of copper, zinc, iron, bismuth, and manganese with sizes between 2 and 54 nm and cubic shapes for copper, zinc, and iron, and spherical shapes (Hosseininassab et al., 2024).

9.7 Biosynthesis of Copper Nanoparticles by Algae

Algae can be employed as stabilizing and reducing agents in the manufacture of nanoparticles, such as iron, gold, copper, and silver nanoparticles. Environmental remediation and nanomedicine are two uses for algae-mediated nanoparticle synthesis, which is a sustainable substitute for traditional chemical processes. This method leverages the unique chemical and biological properties of algae for sustainable and eco-friendly production (Yedoti & Supraja, 2024). In many studies, algae were utilized for the biosynthesis of copper nanoparticles such as *Acanthophora sp.* (Krishnaswamy et al., 2024) and *Coelastrella terrestris* (Khandelwal et al., 2024).

9.8 Characterization of Copper Nanoparticles (Cu NPs)

Metal nanoparticles have unique biological, physical, and chemical properties that distinguish them from bigger particles created of the same material (Modena et al., 2019). These characteristics can be analyzed through characterization, which allows studying and comprehending these unique properties. This is especially vital for

synthesizing new materials and technologies. Furthermore, characterization of metal nanoparticles is important for quality control purposes, as it helps ensure that the produced nanoparticles are safe for use in different applications (Ajose et al., 2022).

There are many different characterization techniques that can be used to study the properties of Cu NPs before they can be used for any application, such as UV-Vis spectroscopy, transmission electron microscopy (TEM), scanning electron microscope (SEM), atomic force microscopy (AFM), Fourier transform infrared spectroscopy (FTIR), atomic absorption spectroscopy (AAS), energy dispersive spectroscopy (EDS), surface-enhanced Raman spectroscopy (SERS), ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD), high-angle annular dark-field (HAADF), dynamic light scattering (DLS), and Zeta potential (Rafique et al., 2017; Vijayaram et al., 2024). These techniques are discussed in detail below.

9.8.1 UV-Vis Spectroscopy Analysis

UV-Vis spectroscopy analysis is one common method for analyzing Cu NP. The analysis includes measuring the light absorption in the UV-Vis area of the electromagnetic band with a spectral range of 200–800 nm. Cu NP can be characterized by a visible shift in color according to the surface plasmon resonance (SPR) concept. This results from surface plasmon absorption caused by the coupled resonance of the metal oxides' open electron band, which is stimulated by the incident UV light.

The change in color metal nanoparticles is caused by surface localized plasmon resonance (SLPR), which occurs in the observable portion of the electromagnetic band (Memon et al., 2020; Hussein et al., 2022). Many studies reported the formation of synthesized CuNPs utilizing the bacterium *Bacillus cereus*, which displayed surface plasmon resonance (SPR) ranging from 570 to 620 nm and 350 to 370 nm (Tiwari et al., 2016). The general peaks for synthesized Cu NPs in UV-visible spectroscopy are shown by strong peak absorption at 567 nm (Pham et al., 2019).

Guru Bharathi et al. (2022) found the UV-Vis absorption peak of biosynthesis CuNPs by *Xenorhabdus* sp. at 335 nm band. Other investigations have also reported the presence of a peak around these wavelengths for Cu NPs synthesized by various approaches (Mohamed, 2020). However, it is very important to note that the change in the precise location of the SPR band may be affected by particle parameters such as size, shape, protecting agents, mass of the NPs, and the used method for synthesizing nanoparticles.

9.8.2 Transmission Electron Microscopy (TEM)

Transmission electron microscopy (TEM) is the best characterization technique for determination of morphology of NPs by examination the particle size of material at the nanoscale level, and crystal structure. Cu NPs can be characterized by TEM for

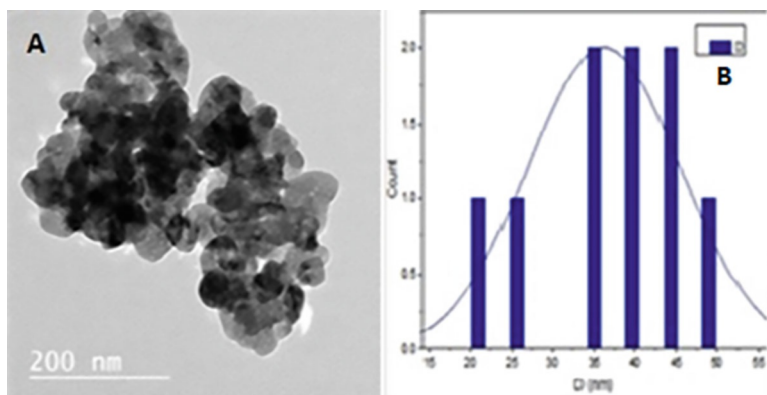


Fig. 9.3 (a) shows a TEM picture of Cu_2O nanoparticles synthesized by *Streptomyces thermolilacinus*, (b) particle-size distribution of produced nanoparticles (Mohamed et al., 2023)

utilization in various uses. The shape and size of Cu NPs were studied by the TEM, and shape was found to be spherical and hexagonal with size 20–80 nm (Rafique et al., 2017; Habeeb Rahuman et al., 2022). In Fig. 9.3 Mohamed et al. (2023) showed a TEM image and particle size distribution of Cu_2O nanoparticles synthesized by *Streptomyces thermolilacinus*.

9.8.3 Scanning Electron Microscope (SEM)

Scanning electron microscopy (SEM) is another method that is applied to study the morphology of nanoparticles (NPs), such as size, shape, orientation, and chemical composition of materials. It has different advantages for the analysis of the morphological properties of metal nanoparticles (Mt NPs). But it also has some disadvantages, such as giving limited information about true population, average, and size distribution (Harishchandra et al., 2020; Wu et al., 2022). The morphology of CuNPs has been investigated by SEM, and micrographs of CuONPs showed a spherical shape with very little agglomeration with a size 5–30 nm.

9.8.4 Atomic Force Microscopy (AFM)

This technique is utilized to investigate qualitative and quantitative data based on various characteristics such as texture, size, surface roughness, and shape compared to other techniques. It is used for the 3D characterization of Mt. NPs, provides data about the geometry of NPs, analysis of hydrated NPs, and physical properties such as magnetic properties, and is used for the study of hard and soft synthetic materials regardless of their opaqueness and conductivity.

However, there are particular limitations of AFM. The resolution is not good if the probe is not sharp enough; then it could not demonstrate the correct topography of the sample, and the probe tip interaction with the sample surface is called tip convolution. The convolution affects the map's vertical resolution compared to its peak.

This technique is slower as compared to other microscopic approaches. This technique is also used to analyze the shape and topography of different materials, such as chitosan, silicon, and composites of Cu NPs and ZnO. For example, Cu NPs with size 23.5 nm were analyzed by AFM (Das et al., 2013; Rafique et al., 2017; Habeeb Rahuman et al., 2022).

9.8.5 Fourier Transforms Infrared Spectroscopy (FTIR)

This spectroscopy technique investigates the functional groups present on the surface of NPs by detecting the vibrational frequency of the bonding present in the functional group. Infrared red rays are used in FTIR analysis. The sample absorbs some of the IR rays while the rest of the rays flow through it. The spectrum describes the sample substances by showing absorption or transmission as a function of wavelength. The molecules react to infrared radiation in the range of 1013–1014 Hz, which allows us to examine the functional groups such as amino groups, phenolic groups, and carboxylate groups. This technique can be applied to study the spectrum of different Mt. NPs such as zinc oxide, gold, silver, and copper NPs (Harishchandra et al., 2020; Chakraborty et al., 2022; Rozali et al., 2023; Javid-Naderi et al., 2023).

9.8.6 X-Ray Diffraction (XRD)

X-ray diffraction (XRD) is primarily used to characterize any crystalline material and determine its structure, or how the atoms are arranged in the crystal structure, as well as the interatomic distance and angle. This technique is used to constructive and destructive interference produced by the crystal lattice structure to resolve molecules at the atomic level that caused by the atom in the lattice. The diffracted pattern of constructive interference by the crystal structure is determined through spacing between planes of atoms and reflection angle.

The Debye-Scherrer equation can be used to determine the crystalline size $D = K\lambda/\cos\theta$, where d is the particle size (nm), K is the Scherrer constant, λ is the wavelength of X-ray, β is the full width half maximum, and θ is the diffraction angle (half of the Bragg angle) that corresponds to the lattice plane. Peak breadth, peak intensity, and peak location (2θ) are responsible for the synergistic effect of lattice strain and crystallite size in the XRD peaks. The crystal structure of CuNPs was studied using a D8 Advance Bruker X-ray diffractometer with Cu $K\alpha$. The average

particle size of NP, as determined by the Debye-Scherrer formula (Crisan et al., 2021; Alaallah et al., 2023; Shitu et al., 2023).

9.8.7 High Angle Annular Dark-Field (HAADF)

The interaction between nanoparticles and microorganisms was identified using annular dark-field imaging (HAADF), which also revealed the size distribution of the nanoparticles engaging with each species of bacteria (Vijayaram et al., 2024).

9.8.8 Dynamic Light Scattering (DLS)

Dynamic light scattering (DLS) is used to measure the size of nanoparticles in colloidal suspension. When utilized to observe the aggregation process in real time, it is an efficient approach. The measurements are precise when combined with differential centrifugal sedimentation (DCS). Its inability to provide the required resolution when dealing with small aggregates is a disadvantage. However, its ability to measure at once various nanoparticle sizes makes it potent (Crisan et al., 2021).

9.8.9 Zeta Potential

The Zeta potential method is used to investigate the surface charge indirectly and is used to analyze the colloidal stability of NPs. It connects the potential variation on the surface of shear and the external Helmholtz plane. The estimate of the zeta potential takes advantage of the colloidal dispersion's storage capacity. The zeta potential measurements can then be used to estimate the degree of surface hydrophobicity. Additionally, the zeta potential can provide information on how the material is encapsulated within the nanocapsules or coated onto the surface. Zetasizer is utilized to quantify the surface charge on NPs and examine their stability. Cu NPs with an average size of 40–100 nm were examined for positive surface charge/zeta potential (50 mV) and colloidal stability such as gold and silver NPs (Rafique et al., 2017; Kamble et al., 2022).

9.9 Plant Absorption Mechanism for Copper Nanoparticles

Nanoparticles are supplied to plants through two most common ways: the root system or the foliar route. To enter plant cells, both pathways require specific binding or ion transport channels, or endocytosis, carrier proteins. Copper

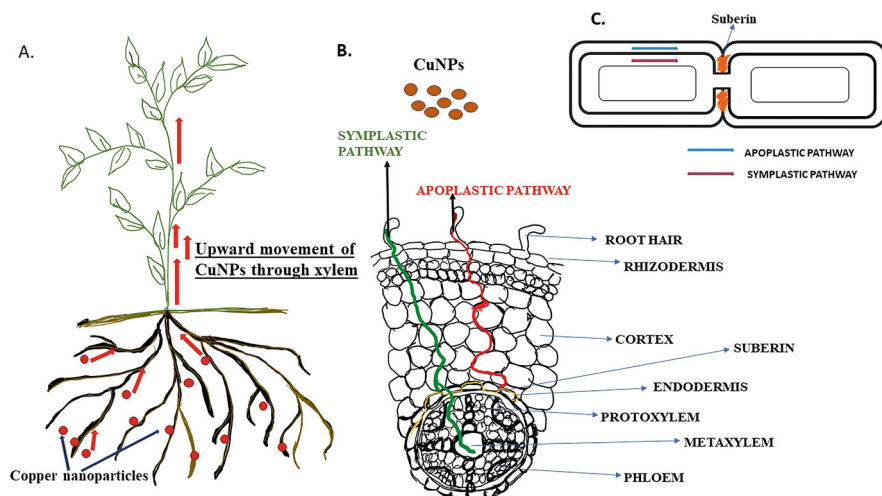


Fig. 9.4 Mechanism of copper nanoparticles absorption in plant cells. (a). Upward movement of Cu NPs in plants by xylem (b). Uptake of Cu NPs through root hairs to the vascular system (c). Two pathways for movement of Cu NPs in the plant cells (Bhagat et al., 2021)

nanoparticles are absorbed by plants from their root hairs and transported through the vascular system to their upper sections. Depending on their size, shape and properties, the particles follow either apoplastic or symplastic paths (Fig. 9.4). There are reports of the presence of specific heavy metal transporters in plants that function in tandem with chelator or sequester transporters, despite the fact that little research has been done on the transport of copper within cells. Plants have been found to use the P-type ATPase Cu transporter to transport both toxic and necessary copper across their cellular membranes (Shabbir et al., 2020; Bhagat et al., 2021).

According to some research, the bulk of the Cu^{2+} that plants absorb is collected as a layer close to the root rhizodermis of *Bambusoideae* (Collin et al., 2014) and *Elsholtzia splendens* (Xu et al., 2015). According to other research, there was a significant buildup of Cu^{2+} in the vascular tissues of rice (Lu et al., 2019) and *Commelina communis* (Wang et al., 2011).

After being absorbed by plants, copper (Cu) is primarily transported to different organs, tissues, and organelles to support healthy growth. Research indicates substantial variability in Cu concentrations in plants grown in naturally or long-term Cu-contaminated soils compared to those cultivated in artificially contaminated pots or hydroponic systems. The average Cu concentration was 31 mg kg^{-1} dry weight in plants grown on naturally contaminated soils, compared to 1048 mg kg^{-1} in pot/hydroponic setups. Furthermore, the maximum Cu concentrations observed were 2016 mg kg^{-1} and $11,247 \text{ mg kg}^{-1}$, respectively (Shabbir et al., 2020). Copper (Cu) enters and moves within plant cells through root absorption, xylem loading, and transport from roots to shoots. These processes of Cu uptake in plant cells are influenced by different ecotypes and plant species (Ghazaryan et al., 2019).

9.10 Application of Copper Nanoparticle in Plant Protection

Copper is used in agriculture mostly in the role of plant protector against bacterial and fungal diseases. About a third of the world's plant harvest is forecast to be lost each year because of a combination of plant diseases caused by bacteria, fungus, viruses and insects. In specific, over thousands of years, copper is employed in many mixtures to mitigate the risk of infection. Recently, copper nanoparticles (Cu NPs) have been described as a cost-effective substitute for other metal and metal oxide nanoparticles in a number of application fields (Chawla et al., 2020). The employ of Cu NPs as a plant pathogen control agent has different advantages compared to traditional chemical pesticides. Firstly, Cu NPs are less likely to harm non-target organisms such as beneficial and pollinators' insects. Secondly, Cu NPs are less toxic to the environment and have a lower risk of developing resistance to pathogens (Kashyap et al., 2023).

Of those mentioned above, copper sulfate is most common as it possesses antifungal properties and is used in making the bulk of the garden and farm fungicides sold in the market today. Typically, the plants were sprayed with copper sulfate or lime, or soda ash solution. Cu-based fungicides can interact with lipids leading to generation of highly reactive hydroxyl radicals. (Rai et al., 2018). Consequently, during the past ten years, there has been more extensive study on copper-based nanoparticles on crops as a micronutrient, diseases biocontrol and a pesticide. This antibacterial action is affected by various parameters, including temperature, pH, aeration, and microbial concentration. CuNPs have been shown to suppress viruses, yeasts, and bacteria (Kalińska et al., 2019).

9.10.1 *Nanopesticides*

Nanopesticides represent a promising approach in agriculture, harnessing nanotechnology to improve the delivery, efficacy, and environmental safety of pest control. These nano-scale pesticides can be designed to release active ingredients more precisely and sustainably, reducing the amount of chemicals needed and potentially minimizing their environmental impact. Their nano dimensions allow them to penetrate plant tissues more efficiently and provide a controlled, targeted release, which helps in achieving effective pest management.

In addition, nanopesticides offer new ways to address pesticide resistance, as the nanostructures can be engineered to bypass the defense mechanisms developed by pests. However, the use of nanotechnology in pesticides also raises new questions about environmental interactions, potential accumulation, and long-term effects on ecosystems and human health. Therefore, studying and regulating nanopesticides is essential for maximizing benefits while mitigating potential risks (Smith et al., 2008; Yasur & Rani, 2013; Benelli & Lukehart, 2017).

NP-based (nanoparticle-based) pesticide formulations indeed offer significant advantages over traditional pesticides, as described by Sasson et al. (2007) and Athanassiou et al. (2018):

1. **Increased Solubility:** Nanoparticles can enhance the solubility of active ingredients that are water-insoluble, expanding the range of usable compounds in pest control.
2. **Enhanced Stability:** Nano-formulations help stabilize active ingredients, making them more resilient against environmental factors like heat and light.
3. **Reduction of Toxic Solvents:** Unlike conventional formulations that often require organic solvents, NP-based pesticides can minimize or eliminate these solvents, reducing toxicity.
4. **Controlled Release:** Nanoparticles allow for slow, sustained release of active ingredients, ensuring prolonged efficacy with fewer applications.
5. **Improved Longevity and Reduced Degradation:** Nanoparticles can protect active compounds from premature degradation, enhancing their persistence.
6. **Increased Mobility and Efficacy:** The smaller particle size improves the penetration and distribution of the active ingredient, leading to better pest control.
7. **Extended Surface Area:** A larger surface area increases interactions with pests, potentially increasing the formulation's lifespan and effectiveness.

These features could make NP-based pesticides both more efficient and potentially more environmentally friendly than traditional pesticides.

The growing number of publications and successful case studies in nanopesticide research indeed underscores the promise and potential of these technologies. Nanoemulsions, nanodispersions, and other nanoparticle-based (NP) formulations represent innovative methods that can increase both the efficacy and safety of pest control solutions. These advanced formulations allow for more precise targeting and controlled release, reducing off-target effects and environmental impact.

With ongoing advancements in the formulation, stability, and application of nanopesticides, there's significant optimism that they could revolutionize pest management practices. These improvements in targeted delivery, environmental safety, and reduced usage of toxic solvents or residues are likely to make nanopesticides an attractive alternative to conventional chemical pesticides. The shift towards nanotechnology-driven pesticides could pave the way for a new generation of sustainable agricultural practices.

9.10.2 Nano-Copper Pesticides

According to Solorzano Toala et al. (2024), copper nanoparticles formed from *Acacia cornigera* and *Annona purpurea* displayed strong insecticidal action against *Tribolium castaneum*. Malandrakis et al. (2024) also found that the insecticide's effectiveness against *Bactrocera oleae* adults was much increased when Cu-NPs or copper oxide nanoparticles (CuO-NPs) were combined with deltamethrin. Cu-NPs considerably decreased the mean total number of offspring as compared to the

control, as well as the number of stings, pupae, females, and offspring when compared to the insecticide alone when used in conjunction with deltamethrin.

The study by El-Ashry et al. (2024) suggests that the application of biosynthesized copper nanoparticles (BCuNPs) at a concentration of 250 ppm, whether used alone or in combination with the nematocide abamectin, can be effective in controlling nematodes that infest cucumber plants. This combination within integrated pest management (IPM) systems shows potential for managing nematode populations with enhanced efficacy while reducing reliance on chemical nematicides.

According to studies by Hemalatha et al. (2024), silver and copper nanoparticles at 1000 ppm have the potential to be useful instruments for managing storage pests and enhancing agricultural sustainability and productivity.

Copper oxide nanoparticles (CuO NPs) exhibit significant larvicidal and antifeedant properties and are therefore effective as environmentally friendly, pollutant-free nanoinsecticides specifically against *Spodoptera frugiperda*, a common and destructive agricultural pest, as reported by Rahman et al. (2022).

These findings support the potential of CuO NPs in integrated pest management strategies, where they could minimize reliance on traditional chemical pesticides, thus addressing issues like pesticide resistance and environmental contamination.

9.10.3 Copper Nanoparticles as an Antibacterial Against Plant Pathogens

Cu NPs have important role in controlling pathogenic bacteria in the agricultural sector. The mode of action of Cu NPs against phyto-pathogenic microbes is believed to be through their ability to produce reactive oxygen species (ROS) that damage the cell walls and membranes of the pathogens and leading to their death also Cu NPs interact with the metabolic functions of the pathogens and inhibit their enzymatic activities (Kashyap et al., 2023).

In plant protection, many of investigations which indicate biocidal effect of Cu NPs against phytopathogenic bacteria such as *Pseudomonas spp*, *Xanthomonas spp*, and *Ralstonia solanacearum* (Chen et al., 2019).

In other studies, Varympopi et al. (2020) found that, Cu NPs have antibacterial activity against seven important phytopathogens in vitro, and Varympopi et al. (2022) demonstrated that Cu NPs had a good antimicrobial activity against bacterial leaf spot disease of tomato *Xanthomonas campestris* pv. *vesicatoria* (Xcv).

9.10.4 Copper Nanoparticles as an Antifungal Agent Against Plant Pathogens

Pathogenic fungi cause a range of diseases in a number of plant species. By the approaches for the control of plant pathogens, the most common application of

fungicides is site-specific. However, the target fungi could develop various defenses against pesticides; this implies that plant pathogenic fungus could develop mutations to become resistant to fungicides, hence reducing the effectiveness of fungicides (Malcolm et al., 2013).

So, uses of various nanoparticles (NPs) for the treatment of plant diseases have been investigated. For example, Cu NPs have the potential to be a powerful fungicide for use in plant protection. Various studies reported that Cu-NPs are used as a fungicide against a variety of species of plant pathogenic fungi such as *Alternaria alternata*, *Alternaria solani*, *Curvularia lunata*, *Corynespora cassiicola*, *Rhizoctonia solani*, *Fusarium* sp. *Fusarium oxysporum*, *Penicillium digitatum*, *Penicillium italicum*, and *Phoma destructive* (Pariona et al., 2019; Yadava et al., 2024).

9.11 Prospects for the Future

Nanopesticides represent a promising approach in agriculture, harnessing nanotechnology to improve the delivery, efficacy, and environmental safety of pest control. These nano-scale pesticides can be designed to release active ingredients more precisely and sustainably, reducing the amount of chemicals needed and potentially minimizing their environmental impact. Their nano dimensions allow them to penetrate plant tissues more efficiently and provide a controlled, targeted release, which helps in achieving effective pest management.

In addition, nanopesticides offer new ways to address pesticide resistance, as the nanostructures can be engineered to bypass the defense mechanisms developed by pests. However, the use of nanotechnology in pesticides also raises new questions about environmental interactions, potential accumulation, and long-term effects on ecosystems and human health. Therefore, studying and regulating nanopesticides is essential for maximizing benefits while mitigating potential risks.

With ongoing advancements in the formulation, stability, and application of nanopesticides, there's significant optimism that they could revolutionize pest management practices. These improvements in targeted delivery, environmental safety, and reduced usage of toxic solvents or residues are likely to make nanopesticides an attractive alternative to conventional chemical pesticides. The shift towards nanotechnology-driven pesticides could pave the way for a new generation of sustainable agricultural practices.

The promising outlook for nanopesticide-based formulations, such as nanoemulsions, nanodispersions, and other nanoparticles, is tempered by important regulatory and safety considerations. These innovative pesticides have the potential to transform pest management by offering safer and more effective alternatives to traditional chemicals. However, as nanomaterials introduce unique risks that are not yet fully understood—particularly concerning their toxicity, environmental persistence, and impacts on human health—there will likely be substantial regulatory scrutiny. Both national and international regulatory bodies are expected to call for

more comprehensive research on the environmental and health implications of nanopesticides.

Additionally, while laboratory-scale research in plant-mediated nanoparticle synthesis for pest control has shown promising results, the practical application of these methods on a large scale remains challenging. Addressing this gap between research and real-world application is crucial for advancing nanopesticides from theoretical promise to practical, sustainable solutions in agriculture (Benelli, 2015).

The synthesis of nanomaterials is a crucial process, and modifications to the synthesis technique may result in modifications to the materials' dimensions and shape as well as the hazards connected with their use. Risk assessment studies are necessary before using such materials. This is because it is necessary to study the compounds' hazardous nature to plants and insects.

Before nanopesticide formulations are used more widely in pest management, a lot of work needs to be done to combine analytical techniques that can detect, characterize (e.g. by size, size range, shape or nature, and surface properties), and quantify the active ingredient and adjuvants that are released from the formulations. Nanotechnology holds transformative potential for agriculture by promoting eco-friendly and cost-effective practices through precision in crop protection and nutrient management. Innovations such as nanosensors enable real-time monitoring of soil health, crop growth stages, and pest or disease activity, allowing for timely, targeted interventions. Smart delivery systems for fertilizers, pesticides, and growth regulators can optimize input usage, reducing the environmental footprint and enhancing crop productivity. Though the pace of progress has been gradual, these advancements suggest a promising future for nanotechnology in agriculture. The potential to significantly reduce reliance on traditional chemical applications while enhancing crop yield aligns with global goals for sustainable agriculture. As research and development continue, we can expect more breakthroughs that will contribute to both environmental sustainability and agricultural profitability (Athanassiou et al., 2018).

9.12 Conclusion

The synthesis of copper-containing NPs continues to be an area of active research due to their multifunctionality and effectiveness in various applications. Their role in sustainable agriculture, particularly through optimized pest control strategies and reducing reliance on chemical pesticides, points to a promising future in increasing agricultural productivity while addressing environmental concerns. Given the growing importance of sustainability, the biological synthesis of metallic nanoparticles is gaining importance as a viable alternative to conventional methods. By utilizing naturally occurring resources, this approach not only promotes environmental friendliness but also contributes to the creation of high-yield and non-toxic products that are valuable for various scientific and industrial applications. Future research will likely focus on optimizing these biological processes to increase yield and efficiency while ensuring environmental safety.

References

- Ahiwale, S. S., Bankar, A. V., Tagunde, S., & Kapadnis, B. P. (2017). A bacteriophage mediated gold nanoparticles synthesis and their anti-biofilm activity. *Indian Journal of Microbiology*, 57, 188–194.
- Ajose, D. J., Abolarinwa, T. O., Oluwarinde, B. O., Montso, P. K., Fayemi, O. E., Aremu, A. O., & Ateba, C. N. (2022). Application of plant-derived nanoparticles (PDNP) in food-producing animals as a bio-control agent against antimicrobial-resistant pathogens. *Biomedicine*, 10(10), 2426.
- Akintelu, S. A., Folorunso, A. S., Folorunso, F. A., & Oyebamiji, A. K. (2020). Green synthesis of copper oxide nanoparticles for biomedical application and environmental remediation. *Heliyon*, 6(7), e04508.
- Alaallah, N. J., Abd Alkareem, E., Ghaidan, A., & Imran, N. A. (2023). Eco-friendly approach for silver nanoparticles synthesis from lemon extract and their anti-oxidant, anti-bacterial, and anti-cancer activities. *Journal of the Turkish Chemical Society Section A: Chemistry*, 10(1), 205–216.
- Al-Qaissi, A. R., Fouzi, S. H., & AL-Baytay, A. J. (2024). Characterization of biologically synthesized copper nanoparticles by *Aspergillus carbonarius* and evaluation of their activity in reducing the pathogenic stress of tomatoes infected with *Fusarium oxysporum*. *Tikrit Journal for Agricultural Sciences*, 24(2), 161–177.
- Antonio-Pérez, A., Durán-Armenta, L. F., Pérez-Loredo, M. G., & Torres-Huerta, A. L. (2023). Biosynthesis of copper nanoparticles with medicinal plants extracts: From extraction methods to applications. *Micromachines*, 14(10), 1882.
- Arakawa, F. S., Shimabuku-Biadola, Q. L., Fernandes Silva, M., & Bergamasco, R. (2020). Development of a new vacuum impregnation method at room atmosphere to produce silver-copper oxide nanoparticles on activated carbon for antibacterial applications. *Environmental Technology*, 41(18), 2400–2411.
- Araújo, I. M., Silva, R. R., Pacheco, G., Lustri, W. R., Tercjak, A., Gutierrez, J., et al. (2018). Hydrothermal synthesis of bacterial cellulose-copper oxide nanocomposites and evaluation of their antimicrobial activity. *Carbohydrate Polymers*, 179, 341–349.
- Athanassiou, C. G., Kavallieratos, N. G., Benelli, G., Losic, D., Usha Rani, P., & Desneux, N. (2018). Nanoparticles for pest control: Current status and future perspectives. *Journal of Pest Science*, 91, 1–15.
- Batool, F., Shahid, M., Mahmood, F., Shahzad, T., Azeem, F., Hussain, S., et al. (2024). Biosynthesis of copper nanoparticles using *Bacillus flexus* and estimation of their potential for decolorization of azo dyes and textile wastewater treatment. *Journal of King Saud University-Science*, 36(8), 103309.
- Benelli, G. (2015). Research in mosquito control: Current challenges for a brighter future. *Parasitology Research*, 114(8), 2801–2805.
- Benelli, G., & Lukehart, C. M. (2017). Applications of green-synthesized nanoparticles in pharmacology, parasitology and entomology. *Journal of Cluster Science*, 28, 1–2.
- Bhagat, M., Anand, R., Sharma, P., Rajput, P., Sharma, N., & Singh, K. (2021). Multifunctional copper nanoparticles: Synthesis and applications. *ECS Journal of Solid State Science and Technology*, 10(6), 063011.
- Bukhari, S. I., Hamed, M. M., Al-Agamy, M. H., Gazwi, H. S., Radwan, H. H., & Youssif, A. M. (2021). Biosynthesis of copper oxide nanoparticles using *Streptomyces* MHM38 and its biological applications. *Journal of Nanomaterials*, 2021(9), 1–16.
- Chakraborty, N., Banerjee, J., Chakraborty, P., Banerjee, A., Chanda, S., Ray, K., et al. (2022). Green synthesis of copper/copper oxide nanoparticles and their applications: A review. *Green Chemistry Letters and Reviews*, 15(1), 187–215.
- Chawla, P., Kumar, N., Bains, A., Dhull, S. B., Kumar, M., Kaushik, R., & Punia, S. (2020). Gum arabic capped copper nanoparticles: Synthesis, characterization, and applications. *International Journal of Biological Macromolecules*, 146, 232–242.

- Chen, J., Mao, S., Xu, Z., & Ding, W. (2019). Various antibacterial mechanisms of biosynthesized copper oxide nanoparticles against soilborne *Ralstonia solanacearum*. *RSC Advances*, 9(7), 3788–3799.
- Chhipa, H. (2019). Applications of nanotechnology in agriculture. In *Methods in microbiology* (Vol. 46, pp. 115–142). Academic.
- Choi, Y., & Lee, S. Y. (2020). Biosynthesis of inorganic nanomaterials using microbial cells and bacteriophages. *Nature Reviews Chemistry*, 4(12), 638–656.
- Collin, B., Doelsch, E., Keller, C., Cazeville, P., Tella, M., Chaurand, P., et al. (2014). Evidence of sulfur-bound reduced copper in bamboo exposed to high silicon and copper concentrations. *Environmental Pollution*, 187, 22–30.
- Crisan, M. C., Teodora, M., & Lucian, M. (2021). Copper nanoparticles: Synthesis and characterization, physiology, toxicity and antimicrobial applications. *Applied Sciences*, 12(1), 141.
- Cuevas, R., Durán, N., Diez, M. C., Tortella, G. R., & Rubilar, O. (2015). Extracellular biosynthesis of copper and copper oxide nanoparticles by *Stereum hirsutum*, a native white-rot fungus from Chilean forests. *Journal of Nanomaterials*, 2015(1), 789089.
- Das, J., Das, M. P., & Velusamy, P. (2013). *Sesbania grandiflora* leaf extract mediated green synthesis of antibacterial silver nanoparticles against selected human pathogens. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 104, 265–270.
- Das, R. K., Pachapur, V. L., Lonappan, L., Naghdi, M., Pulicharla, R., Maiti, S., et al. (2017). Biological synthesis of metallic nanoparticles: Plants, animals and microbial aspects. *Nanotechnology For Environmental Engineering*, 2, 1–21.
- Devra, V. (2022). Applications of metal nanoparticles in the agri-food sector. *Egyptian Journal of Agricultural Research*, 100(2), 163–183.
- Dorjee, L., Kamil, D., Kumar, R., Khokhar, M. K., Aggarwal, R., & Gogoi, R. (2024). Synthesis of promising copper nanoparticles utilizing biocontrol agents, *Trichoderma virens* and *Chaetomium globosum*. *The Indian Journal of Agricultural Sciences*, 94(1), 061–067.
- El-Ashry, R. M., Nader, M. M., Shami, A., Alduwish, M. A., Ahmed, A. E., Alamoud, S. A., et al. (2024). Ecofriendly synthesis and nematicidal application of copper nanoparticles fabricated from *Bacillus subtilis* AM18, against root-knot nematode of cucumber. *European Journal of Plant Pathology*, 168(1), 53–81.
- El-Batal, A. I., Al-Hazmi, N. E., Mosallam, F. M., & El-Sayyad, G. S. (2018). Biogenic synthesis of copper nanoparticles by natural polysaccharides and *Pleurotus ostreatus* fermented fenugreek using gamma rays with antioxidant and antimicrobial potential towards some wound pathogens. *Microbial Pathogenesis*, 118, 159–169.
- Erci, F., Cakir-Koc, R., Yontem, M., & Torlak, E. (2020). Synthesis of biologically active copper oxide nanoparticles as promising novel antibacterial-antibiofilm agents. *Preparative Biochemistry & Biotechnology*, 50(6), 538–548.
- Ghazaryan, K., Movsesyan, H., Ghazaryan, N., & Watts, B. A. (2019). Copper phytoremediation potential of wild plant species growing in the mine polluted areas of Armenia. *Environmental Pollution*, 249, 491–501.
- Ghorbani, H. R., Fazeli, I., & Fallahi, A. A. (2015). Biosynthesis of copper oxide nanoparticles using extract of *E. coli*. *Oriental Journal of Chemistry*, 31(1), 515–517.
- Grasso, G., Zane, D., & Dragone, R. (2019). Microbial nanotechnology: Challenges and prospects for green biocatalytic synthesis of nanoscale materials for sensoristic and biomedical applications. *Nanomaterials*, 10(1), 11.
- Guru Bharathi, B., Lalitha, K., & Shivakumar, M. S. (2022). Biosynthesis of copper nanoparticles using symbiotic bacterium *Xenorhabdus* sp, isolated from entomopathogenic nematode and its antimicrobial and insecticidal activity against *Spodoptera litura*. *Inorganic and Nano-Metal Chemistry*, 54(9), 1–13.
- Habeeb Rahuman, H. B., Dhandapani, R., Narayanan, S., Palanivel, V., Paramasivam, R., Subbarayalu, R., & Muthupandian, S. (2022). Medicinal plants mediated the green synthesis of silver nanoparticles and their biomedical applications. *IET Nanobiotechnology*, 16(4), 115–144.

- Harishchandra, B. D., Pappuswamy, M., Antony, P. U., Shama, G., Pragatheesh, A., Arumugam, V. A., & Sundaram, R. (2020). Copper nanoparticles: A review on synthesis, characterization and applications. *Asian Pacific Journal of Cancer Biology*, 5(4), 201–210.
- Hassan, S. E. D., Fouda, A., Radwan, A. A., Salem, S. S., Barghoth, M. G., Awad, M. A., et al. (2019). Endophytic actinomycetes streptomyces spp mediated biosynthesis of copper oxide nanoparticles as a promising tool for biotechnological applications. *JBIC Journal of Biological Inorganic Chemistry*, 24(3), 377–393.
- Hemalatha, M., Hilli, J. S., Chandrashekhar, S. S., Vijayakumar, A. G., Reddy, U. G., & Tippannavar, P. S. (2024). Application of green synthesized Ag and Cu nanoparticles for the control of bruchids and their impact on seed quality and yield in greengram. *Heliyon*, 10(11), e31551.
- Honary, S., Barabadi, H., Gharaei-Fathabad, E., & Naghibi, F. (2012). Green synthesis of copper oxide nanoparticles using *Penicillium aurantiogriseum*, *Penicillium citrinum* and *Penicillium waksmanii*. *Digest Journal of Nanomaterials and Biostructures*, 7(3), 999–1005.
- Hosseini, M. R., Schaffie, M., Pazouki, M., Darezereshki, E., & Ranjbar, M. (2012). Biologically synthesized copper sulfide nanoparticles: Production and characterization. *Materials Science in Semiconductor Processing*, 15(2), 222–225.
- Hosseininassab, S. S., Naderifar, M., Akbarizadeh, M. R., Rahimzadeh, M., Soltaninejad, S., Makarem, Z., & Sadeghi Dousari, A. (2024). The use of phages for the biosynthesis of metal nanoparticles and their biological applications: A review. *Journal of Cellular and Molecular Medicine*, 28(11), e18383.
- Husen, A., & Iqbal, M. (2019). *Nanomaterials and plant potential: An overview* (pp. 3–29). Springer International Publishing.
- Hussein, K. I., Alzuhair, A. Z., Alqahtani, M. S., Meshawi, A. A., Alhifzi, R. Z., Yahia, I. S., & Reben, M. (2022). Optical properties and novelty preparation PVA/PVP doping with Cu as surface plasmonic ions. *Optik*, 259, 168965.
- Ingle, P. U., Shende, S. S., Hande, D., Rai, M., Golinska, P., & Gade, A. K. (2024). Mycogenic copper oxide nanoparticles for fungal infection management in agricultural crop plants. *BioNanoScience*, 14(1), 359–367.
- Jadoun, S., Arif, R., Jangid, N. K., & Meena, R. K. (2021a). Green synthesis of nanoparticles using plant extracts: A review. *Environmental Chemistry Letters*, 19(1), 355–374.
- Jadoun, S., Verma, A., & Arif, R. (2021b). Green synthesis of nanomaterials for textile applications. In *Green chemistry for sustainable textiles* (pp. 315–324). Woodhead Publishing.
- Javid-Naderi, M. J., Sabouri, Z., Jalili, A., Zarrinfar, H., Samarghandian, S., & Darroudi, M. (2023). Green synthesis of copper oxide nanoparticles using okra (*Abelmoschus esculentus*) fruit extract and assessment of their cytotoxicity and photocatalytic applications. *Environmental Technology & Innovation*, 32, 103300.
- Kalińska, A., Jaworski, S., Wierzbicki, M., & Gołębiewski, M. (2019). Silver and copper nanoparticles—An alternative in future mastitis treatment and prevention? *International Journal of Molecular Sciences*, 20(7), 1672.
- Kamble, S., Agrawal, S., Cherumukkil, S., Sharma, V., Jasra, R. V., & Munshi, P. (2022). Revisiting zeta potential, the key feature of interfacial phenomena, with applications and recent advancements. *ChemistrySelect*, 7(1), e202103084.
- Kasana, R. C., Panwar, N. R., Kaul, R. K., & Kumar, P. (2016). Copper nanoparticles in agriculture: Biological synthesis and antimicrobial activity. *Nanoscience in Food and Agriculture*, 3, 129–143.
- Kasana, R. C., Panwar, N. R., Kaul, R. K., & Kumar, P. (2017). Biosynthesis and effects of copper nanoparticles on plants. *Environmental Chemistry Letters*, 15, 233–240.
- Kashyap, P., Shirkot, P., Das, R., Pandey, H., & Singh, D. (2023). Biosynthesis and characterization of copper nanoparticles from *Stenotrophomonas maltophilia* and its effect on plant pathogens and pesticide degradation. *Journal of Agriculture and Food Research*, 13, 100654.
- Khandelwal, M., Choudhary, S., Harish, Kumawat, A., Misra, K. P., Vyas, Y., et al. (2024). An eco-friendly synthesis approach for enhanced photocatalytic and antibacterial properties of copper oxide nanoparticles using *Coelastrella terrestris* algal extract. *International Journal of Nanomedicine*, 19, 4137–4162.

- Khatoon, U. T., Mohan Mantravadi, K., & Nageswara Rao, G. V. S. (2018). Strategies to synthesise copper oxide nanoparticles and their bio applications—a review. *Materials Science and Technology*, 34(18), 2214–2222.
- Kobayashi, M., Tomita, S., Sawada, K., Shiba, K., Yanagi, H., Yamashita, I., & Uraoka, Y. (2012). Chiral meta-molecules consisting of gold nanoparticles and genetically engineered tobacco mosaic virus. *Optics Express*, 20(22), 24856–24863.
- Korbekandi, H., Irvani, S., & Abbasi, S. (2012). Optimization of biological synthesis of silver nanoparticles using *Lactobacillus casei* subsp. *casei*. *Journal of Chemical Technology & Biotechnology*, 87(7), 932–937.
- Kouhkan, M., Ahangar, P., Babaganjeh, L. A., & Allahyari-Devin, M. (2020). Biosynthesis of copper oxide nanoparticles using *Lactobacillus casei* subsp. *casei* and its anticancer and antibacterial activities. *Current Nanoscience*, 16(1), 101–111.
- Krishnaswamy, J., Christupaul Roseline, P., Kannan, K., Dhanraj, G., & Sivaperumal, P. (2024). Biosynthesis, characterization, and anticoagulant properties of copper nanoparticles from red seaweed of *Acanthophora* sp. *Phytochemical Analysis*. <https://doi.org/10.1002/pca.3384>
- Lahiri, D., Nag, M., Sheikh, H. I., Sarkar, T., Edinur, H. A., Pati, S., & Ray, R. R. (2021). Microbiologically-synthesized nanoparticles and their role in silencing the biofilm signaling cascade. *Frontiers in Microbiology*, 12, 636588.
- Lee, H. J., Lee, G., Jang, N. R., Yun, J. H., Song, J. Y., & Kim, B. S. (2011). Biological synthesis of copper nanoparticles using plant extract. *Nanotechnology*, 1(1), 371–374.
- Leong, C. Y., Wahab, R. A., Lee, S. L., Ponnusamy, V. K., & Chen, Y. H. (2023). Current perspectives of metal-based nanomaterials as photocatalytic antimicrobial agents and their therapeutic modes of action: A review. *Environmental Research*, 227, 115578.
- Li, X., Xu, H., Chen, Z. S., & Chen, G. (2011). Biosynthesis of nanoparticles by microorganisms and their applications. *Journal of Nanomaterials*, 2011(1), 270974.
- Lu, K., Cheng, Y., Li, W., Ni, H., Chen, X., Li, Y., et al. (2019). Copper-induced H₂O₂ accumulation confers larval tolerance to xanthotoxin by modulating CYP6B50 expression in *Spodoptera litura*. *Pesticide Biochemistry and Physiology*, 159, 118–126.
- Luque-Jacobo, C. M., Cespedes-Loayza, A. L., Echegaray-Ugarte, T. S., Cruz-Loayza, J. L., Cruz, I., de Carvalho, J. C., & Goyzueta-Mamani, L. D. (2023). Biogenic synthesis of copper nanoparticles: A systematic review of their features and main applications. *Molecules*, 28(12), 4838.
- Lv, Q., Zhang, B., Xing, X., Zhao, Y., Cai, R., Wang, W., & Gu, Q. (2018). Biosynthesis of copper nanoparticles using *Shewanella loihica* PV-4 with antibacterial activity: Novel approach and mechanisms investigation. *Journal of Hazardous Materials*, 347, 141–149.
- Ma, X., Zhou, S., Xu, X., & Du, Q. (2022). Copper-containing nanoparticles: Mechanism of antimicrobial effect and application in dentistry—a narrative review. *Frontiers in Surgery*, 9, 905892.
- Malandrakis, A. A., Varikou, K., Kavroulakis, N., Nikolakakis, A., Dervisi, I., Reppa, C. I., et al. (2024). Copper nanoparticles interfere with insecticide sensitivity, fecundity and endosymbiont abundance in olive fruit fly *Bactrocera oleae* (Diptera: Tephritidae). *Pest Management Science*, 80(7), 3640–3649.
- Malcolm, G. M., Kuldau, G. A., Gugino, B. K., & Jiménez-Gasco, M. D. M. (2013). Hidden host plant associations of soilborne fungal pathogens: An ecological perspective. *Phytopathology*, 103(6), 538–544.
- Memon, R., Memon, A. A., Sherazi, S. T. H., Sirajuddin, S., Balouch, A., Shah, M. R., & Agheem, M. H. (2020). Application of synthesized copper nanoparticles using aqueous extract of *Ziziphus mauritiana* L. leaves as a colorimetric sensor for the detection of Ag. *Turkish Journal of Chemistry*, 44(5), 1376–1385.
- Modena, M. M., Rühle, B., Burg, T. P., & Wuttke, S. (2019). Nanoparticle characterization: What to measure? *Advanced Materials*, 31(32), 1901556.
- Mohamed, E. A. (2020). Green synthesis of copper & copper oxide nanoparticles using the extract of seedless dates. *Heliyon*, 6(1), e03123.

- Mohamed, M. D., El-Deeb, B. A., Mohamed, D. A., Mosa, M. A., & Elsharouny, T. H. (2023). Biosynthesis and antimicrobial activity of copper oxide nanoparticles. *Journal of Sohag Agriscience (JSAS)*, 8(2), 282–295.
- Mostafazade, R., Arabi, L., Tazik, Z., Akaberi, M., & Bazzaz, B. S. F. (2024). Green synthesis of gold, copper, zinc, iron, and other metal nanoparticles by fungal endophytes; characterization, and their biological activity: A review. *Biocatalysis and Agricultural Biotechnology*, 60, 103307.
- Narayanan, K. B., & Sakthivel, N. (2010). Biological synthesis of metal nanoparticles by microbes. *Advances in Colloid and Interface Science*, 156(1–2), 1–13.
- Nassar, A. R. A., Atta, H. M., Abdel-Rahman, M. A., El Naghy, W. S., & Fouda, A. (2023). Mycosynthesized copper oxide nanoparticles using harnessing metabolites of endophytic fungal strain *aspergillus terreus*: An insight into antibacterial, anti-Candida, biocompatibility, anticancer, and antioxidant activities. *BMC Complementary Medicine and Therapies*, 23(1), 261.
- Noor, S., Shah, Z., Javed, A., Ali, A., Hussain, S. B., Zafar, S., et al. (2020). A fungal based synthesis method for copper nanoparticles with the determination of anticancer, antidiabetic and antibacterial activities. *Journal of Microbiological Methods*, 174, 105966.
- Nthunya, L. N., Mbakop, S., Makgabutlane, B., Matlou, G., Mhlanga, S., & Richards, H. (2023). Fungal synthesis of copper nanoparticles and their applications in agri-food, environmental, and biomedical sectors. In *Fungal cell factories for sustainable nanomaterials productions and agricultural applications* (pp. 91–114). Elsevier.
- Ogunyemi, S. O., Abdallah, Y., Ibrahim, E., Zhang, Y., Bi, J. A., Wang, F., et al. (2023). Bacteriophage-mediated biosynthesis of MnO₂NPs and MgONPs and their role in the protection of plants from bacterial pathogens. *Frontiers in Microbiology*, 14, 1193206.
- Ovais, M., Khalil, A. T., Ayaz, M., Ahmad, I., Nethi, S. K., & Mukherjee, S. (2018). Biosynthesis of metal nanoparticles via microbial enzymes: A mechanistic approach. *International Journal of Molecular Sciences*, 19(12), 4100.
- Paczesny, J., & Bielec, K. (2020). Application of bacteriophages in nanotechnology. *Nanomaterials*, 10(10), 1944.
- Pariona, N., Mtz-Enriquez, A. I., Sánchez-Rangel, D., Carrión, G., Paraguay-Delgado, F., & Rosas-Saito, G. (2019). Green-synthesized copper nanoparticles as a potential antifungal against plant pathogens. *RSC Advances*, 9(33), 18835–18843.
- Patel, B. H., Channiwal, M. Z., Chaudhari, S. B., & Mandot, A. A. (2016). Biosynthesis of copper nanoparticles; its characterization and efficacy against human pathogenic bacterium. *Journal of Environmental Chemical Engineering*, 4(2), 2163–2169.
- Patil, S., & Chandrasekaran, R. (2020). Biogenic nanoparticles: A comprehensive perspective in synthesis, characterization, application and its challenges. *Journal of Genetic Engineering and Biotechnology*, 18(1), 67.
- Pham, N. D., Duong, M. M., Le, M. V., & Hoang, H. A. (2019). Preparation and characterization of antifungal colloidal copper nanoparticles and their antifungal activity against *Fusarium oxysporum* and *Phytophthora capsici*. *Comptes Rendus Chimie*, 22(11–12), 786–793.
- Rafique, M., Shaikh, A. J., Rasheed, R., Tahir, M. B., Bakhat, H. F., Rafique, M. S., & Rabbani, F. (2017). A review on synthesis, characterization and applications of copper nanoparticles using green method. *Nano*, 12(04), 1750043.
- Rahman, A., Pittarate, S., Perumal, V., Thungrabeab, M., Mekchay, S., & Krutmuang, P. (2022). Larvicidal and antifeedant effects of copper nano-pesticides against *Spodoptera frugiperda* (JE Smith) and its immunological response. *Insects*, 13(11), 1030.
- Rai, M., Ingle, A., Pandit, R., Paralikal, P., Shende, S., Gupta, I., Biswas, J., & da Silva, S. (2018). Copper and copper nanoparticles: Role in management of insect-pests and pathogenic microbes. *Nanotechnology Reviews*, 7(4), 303–315.
- Rajeshkumar, S., Santhoshkumar, J., Vanaja, M., Sivaperumal, P., Ponnanikajamideen, M., Ali, D., & Arunachalam, K. (2022). Evaluation of zebrafish toxicology and biomedical potential of *aeromonas hydrophila* mediated copper sulfide nanoparticles. *Oxidative Medicine and Cellular Longevity*, 2022, 7969825.

- Ramanathan, R., Field, M. R., O'Mullane, A. P., Smooker, P. M., Bhargava, S. K., & Bansal, V. (2013). Aqueous phase synthesis of copper nanoparticles: A link between heavy metal resistance and nanoparticle synthesis ability in bacterial systems. *Nanoscale*, 5(6), 2300–2306.
- Rawat, R. S. (2015). Dense plasma focus-from alternative fusion source to versatile high energy density plasma source for plasma nanotechnology. *Journal of Physics: Conference Series*, 591(1), 012021. IOP Publishing.
- Rozali, N. L., Azizan, K. A., Singh, R., Jaafar, S. N. S., Othman, A., Weckwerth, W., & Ramli, U. S. (2023). Fourier transform infrared (FTIR) spectroscopy approach combined with discriminant analysis and prediction model for crude palm oil authentication of different geographical and temporal origins. *Food Control*, 146, 109509.
- Sahithya, K., Ekanayake, A. K., Hemanathan, D., Sindhu, R., & Jaswanth, B. (2024). Mycosynthesis of CuO nanoparticles using aspergillus Niger and their bioefficiency against human pathogens. *Nano Biomedicine and Engineering*, 16(2), 264–275.
- Saif Hasan, S., Singh, S., Parikh, R. Y., Dharne, M. S., Patole, M. S., Prasad, B. L. V., & Shouche, Y. S. (2008). Bacterial synthesis of copper/copper oxide nanoparticles. *Journal of Nanoscience and Nanotechnology*, 8(6), 3191–3196.
- Salvadori, M. R., Lepre, L. F., Ando, R. A., Oller do Nascimento, C. A., & Corrêa, B. (2013). Biosynthesis and uptake of copper nanoparticles by dead biomass of *Hypocrea lixii* isolated from the metal mine in the Brazilian Amazon region. *PLoS One*, 8(11), e80519.
- Saona, L. A., Campo-Giraldo, J. L., Anziani-Ostuni, G., Ordenes-Aenishanslins, N., Venegas, F. A., Giordana, M. F., et al. (2022). Cysteine-mediated green synthesis of copper sulphide nanoparticles: Biocompatibility studies and characterization as counter electrodes. *Nanomaterials*, 12(18), 3194.
- Saravanakumar, K., Shanmugam, S., Varukattu, N. B., MubarakAli, D., Kathiresan, K., & Wang, M. H. (2019). Biosynthesis and characterization of copper oxide nanoparticles from indigenous fungi and its effect of photothermolysis on human lung carcinoma. *Journal of Photochemistry and Photobiology B: Biology*, 190, 103–109.
- Sasson, Y., Levy-Ruso, G., Toledano, O., & Ishaaya, I. (2007). Nanosuspensions: Emerging novel agrochemical formulations. In *Insecticides design using advanced technologies* (pp. 1–39). Springer Berlin Heidelberg.
- Shabbir, Z., Sardar, A., Shabbir, A., Abbas, G., Shamshad, S., Khalid, S., et al. (2020). Copper uptake, essentiality, toxicity, detoxification and risk assessment in soil-plant environment. *Chemosphere*, 259, 127436.
- Shantkriti, S., & Rani, P. (2014). Biological synthesis of copper nanoparticles using *Pseudomonas fluorescens*. *International Journal of Current Microbiology and Applied Sciences*, 3(9), 374–383.
- Shitu, I. G., Katibi, K. K., Taura, L. S., Muhammad, A., Chiromawa, I. M., Adamu, S. B., & Iya, S. G. D. (2023). X-ray diffraction (XRD) profile analysis and optical properties of klockmannite copper selenide nanoparticles synthesized via microwave assisted technique. *Ceramics International*, 49(8), 12309–12326.
- Shobha, G., Moses, V., & Ananda, S. (2014). Biological synthesis of copper nanoparticles and its impact. *International Journal of Pharmaceutical Science Invention*, 3(8), 6–28.
- Siddiqi, K. S., Husen, A., & Rao, R. A. (2018). A review on biosynthesis of silver nanoparticles and their biocidal properties. *Journal of Nanobiotechnology*, 16(1), 14.
- Singh, N. A., Narang, J., Garg, D., Jain, V., Payasi, D., Suleman, S., & Swami, R. K. (2023). Nanoparticles synthesis via microorganisms and their prospective applications in agriculture. *Plant Nano Biology*, 5, 100047.
- Smith, K., Evans, D. A., & El-Hiti, G. A. (2008). Role of modern chemistry in sustainable arable crop protection. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1491), 623–637.
- Solorzano Toala, R., Gutierrez-Miceli, F., Valdez-Salas, B., Beltran-Partida, E., Gonzalez-Mendoza, D., Tzintzun-Camacho, O., et al. (2024). Biosynthesis of copper nanoparticles from

- Acacia cornigera* and *Annona purpurea* and their insecticidal effect against *Tribolium castaneum*. *Reactions*, 5(2), 274–284.
- Thakkar, K. N., Mhatre, S. S., & Parikh, R. Y. (2010). Biological synthesis of metallic nanoparticles. *Nanomedicine: Nanotechnology, Biology and Medicine*, 6(2), 257–262.
- Tiwari, M., Jain, P., Hariharapura, R. C., Narayanan, K., Bhat, U., Udupa, N., & Rao, J. V. (2016). Biosynthesis of copper nanoparticles using copper-resistant *Bacillus cereus*, a soil isolate. *Process Biochemistry*, 51(10), 1348–1356.
- ul Ain, N., Nasir, J. A., Khan, Z., Butler, I. S., & Rehman, Z. (2022). Copper sulfide nanostructures: Synthesis and biological applications. *RSC Advances*, 12(12), 7550–7567.
- Varshney, R., Bhadauria, S., Gaur, M. S., & Pasricha, R. (2010). Characterization of copper nanoparticles synthesized by a novel microbiological method. *JOM*, 62, 102–104.
- Varympopi, A., Dimopoulou, A., Theologidis, I., Karamanidou, T., Kaldeli Kerou, A., Vlachou, A., & Skandalis, N. (2020). Bactericides based on copper nanoparticles restrain growth of important plant pathogens. *Pathogens*, 9(12), 1024.
- Varympopi, A., Dimopoulou, A., Papafotis, D., Avramidis, P., Sarris, I., Karamanidou, T., ... & Skandalis, N. (2022). Antibacterial activity of copper nanoparticles against *Xanthomonas campestris* pv. *vesicatoria* in tomato plants. *International Journal of Molecular Sciences*, 23(8), 4080.
- Verma, N., & Kumar, N. (2019). Synthesis and biomedical applications of copper oxide nanoparticles: An expanding horizon. *ACS Biomaterials Science & Engineering*, 5(3), 1170–1188.
- Vijayaram, S., Razafindralambo, H., Sun, Y. Z., Vasantharaj, S., Ghafarifarsani, H., Hoseinifar, S. H., & Raeesazadeh, M. (2024). Applications of green synthesized metal nanoparticles—A review. *Biological Trace Element Research*, 202(1), 360–386.
- Wang, S. H., Zhang, H., Zhang, Q., Jin, G. M., Jiang, S. J., Jiang, D., et al. (2011). Copper-induced oxidative stress and responses of the antioxidant system in roots of *Medicago sativa*. *Journal of Agronomy and Crop Science*, 197(6), 418–429.
- Waris, A., Din, M., Ali, A., Ali, M., Afridi, S., Baset, A., & Khan, A. U. (2021). A comprehensive review of green synthesis of copper oxide nanoparticles and their diverse biomedical applications. *Inorganic Chemistry Communications*, 123, 108369.
- Wen, L., Lin, Z., Gu, P., Zhou, J., Yao, B., Chen, G., & Fu, J. (2009). Extracellular biosynthesis of monodispersed gold nanoparticles by a SAM capping route. *Journal of Nanoparticle Research*, 11, 279–288.
- Wu, X., Fang, F., Zhang, B., Wu, J. J., & Zhang, K. (2022). Biogenic silver nanoparticles-modified forward osmosis membranes with mitigated internal concentration polarization and enhanced antibacterial properties. *npj Clean Water*, 5(1), 41.
- Xu, C., Chen, X., Duan, D., Peng, C., Le, T., & Shi, J. (2015). Effect of heavy-metal-resistant bacteria on enhanced metal uptake and translocation of the Cu-tolerant plant, *Elsholtzia splendens*. *Environmental Science and Pollution Research*, 22, 5070–5081.
- Yadava, Y. P., Raju, V., Chathoth, A. M., Vasu, A. E., Vijayaraghavan, R., & Surendran, A. K. (2024). Characterization and antifungal potential of green-synthesized copper nanoparticles using waste leaf biomass. *Chemical Papers*, 79, 5261–5275.
- Yasur, J., & Rani, P. U. (2013). Environmental effects of nanosilver: Impact on castor seed germination, seedling growth, and plant physiology. *Environmental Science and Pollution Research*, 20, 8636–8648.
- Yedoti, V., & Supraja, N. (2024). A review on algal mediated synthesized metallic nanoparticles: An eco-friendly approach for sustainable nanotechnology. *Current Journal of Applied Science and Technology*, 43(6), 1–10.
- Zeng, Q., Wen, H., Wen, Q., Chen, X., Wang, Y., Xuan, W., et al. (2013). Cucumber mosaic virus as drug delivery vehicle for doxorubicin. *Biomaterials*, 34(19), 4632–4642.
- Zhou, N. Q., Tian, L. J., Wang, Y. C., Li, D. B., Li, P. P., Zhang, X., & Yu, H. Q. (2016). Extracellular biosynthesis of copper sulfide nanoparticles by *Shewanella oneidensis* MR-1 as a photothermal agent. *Enzyme and Microbial Technology*, 95, 230–235.

Chapter 10

Phytotoxic Effects of Nanobased Materials and Defense Mechanisms in Plants



Hany H. A. El-Sharkawy and Adel Kamel Madbouly

Abstract Nano-based materials (NBMs) have special physicochemical properties, which offer them a wealth of opportunities in the field of agriculture. The interaction of NBMs with plants causes a variety of physiological, morphological, and genotoxic changes; understanding these effects is crucial for the efficient application of nanotechnology in agriculture. Researchers suggested that, depending on the properties of the NBMs, the mode of application, and species of the plant, there may be positive or negative impacts of NBMs on development and growth of plant. Recent research efforts involve *in vivo* studies in the field on the uptake, translocation, biotransformation, and risks of applying NBMs on the agricultural crops. In spite of the beneficial uses of NBMs in our daily life; however, their excessive usage at elevated concentrations displays deleterious effects; mainly phytotoxicity. NBMs induced phytotoxicity affects several aspects of the agricultural sector, including induction of oxidative stress, poor seed germination and reduced biomass yield, disruption of the photosynthetic machinery, alters gene expression, affects plant cell membrane integrity, causes damage to DNA, and elicits epigenetic variations in the affected plants. To understand comprehensively the physiological, biochemical, and molecular mechanisms of NBMs induced phytotoxicity, this review aims to study the various mechanisms of NBMs phytotoxicity, NBMs translocation and transfer within the root and leaves, effect on growth parameters (*i.e.*, chlorophyll contents and total pigments) and yield of the plants, different defense mechanisms employed by the affected plants, induced deleterious molecular changes in the plant cell, and cell genotoxicity.

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10.1 Introduction

Plants are the primary resources of food, feed, fuel, chemicals, and medicines. Maintaining healthy plant growth is essential not only for agriculture, but also for survival of humans and animals. Various physicochemical, biotic, and abiotic stresses threaten plant growth and production. Plant cells have defense mechanisms that act to sense and respond rapidly to the various environmental stresses. There is a growing interest in using nanotechnology to enhance growth and yield of crop plant, and tolerance to the various stresses (Ali et al., 2021). However, the effects of many NBMs on plants remain relatively unexplored. In spite of the beneficial effects of NBMs in sustainable and smart agriculture; however, concerns have arisen about the potentially toxic effects of NBMs resulting from their harmful properties. Uptake of NBMs through specific routes such as root and leaf uptake could be harmful to plants. In the context of phytotoxic effects of NBMs, Khan et al. (2021) study focused on the impacts of carbon-based, quantum dots, and metal and metal oxide nanoparticles (NPs) on the economic plants (Khan et al., 2021).

In recent years, nanotechnology received a considerable amount of interest due to its great potential in the different fields such as engineering, biomedicine, and materials science. Nanotechnology has also progressed in the agricultural research. Multiple number of studies recently focused on the improvement of crop production and water use efficiency, postharvest storage, protection against plant pathogens, and soil analysis and remediation by employing nanotechnology (Li et al., 2020). Researches have also shown that plants can uptake and accumulate NPs along with their subcellular biological responses. Another emerging interest in plant research related to nanotechnology involves the potential phytotoxic effects of various NBMs (Rahman et al., 2022).

Materials with at least one dimension smaller than 100 nm are referred to as NBMs (Gao et al., 2023). NBMs have distinct physicochemical features compared to their bulk forms (Xu et al., 2020), which are typically brought about by their sub-size, structure of their surfaces, chemical composition, and appearance, in addition to aggregation, as revealed in the study conducted by Wang et al. (2016). Due to these features, NBMs have achieved remarkable success in a variety of applications, including the food sector, environmental cleanup, and energy generation (Pathakoti et al., 2018). As NBMs are extensively used, there is an inevitable increase in likelihood of being released into the environment during waste's disposal, production, and recycling, which leads to buildup of NBMs in the ecosystems (Alimi et al., 2018). NBMs are absorbed from the soil by plants through their roots and/or leaves by stomata that offer additional opportunities for leaf absorption, because their size are substantially bigger than the openings present in other plant

barriers such as cell walls. This suggests that plants may be able to absorb NBMs through up-to-down or down-to-up pathways (Ha et al., 2021). When employed in safe concentrations, some NPs can improve plant growth and increase crop productivity. However, more negative effects of NPs have been recently documented. These include damage of plant roots, suppression of photosynthesis, and inhibition of seed germination (Singla et al., 2019). After being absorbed by plants, NBMs can move through the vascular system to the other tissues where they may cause oxidative stress, reduction in activity of antioxidant enzymes, micronucleus and chromosomal aberration index enhancement, and other cytotoxic and genotoxic effects, which ultimately affect plant root elongation and seed germination (Khan et al., 2019a). The toxicity of NBMs has garnered a lot of attention lately. Plants exposed to NBMs may migrate into the food web and experience high-level of enrichment, which could be harmful to the human health (Rajput et al., 2020a). Additionally, the buildup of NPs has a negative impact on nutrient intake and plant development, which lowers crop productivity (Lian et al., 2021). The amount of toxicity resulting from released Cu ions and nanoscale particles is still up for debate, notwithstanding reports of CuO-NPs phytotoxicity on several plant species. According to Ameh and Sayes (2019), bioaccumulation of Cu in plants, degree of oxidative stress, and bioactivity are all impacted by the physicochemical properties of CuO-NPs, including solubility, size, and surface functionalization. Joško et al. (2021) reported that barley (*Hordeum vulgare* L.) biomass declined following a 7-day treatment with CuO-NPs at a dose of 300 mg/kg soil; conversely, a combined exposure to nanoscale CuO and ZnO produced a comparable reduction of about 25%.

In this chapter, we seek to examine the potentially positive or negative physiological/biochemical modifications of plants due to exposure/post-application of NPs, and discuss the induction of defense mechanisms to avoid their harmful impacts. The objective of this study is to emphasize the information that report the adverse impacts of NPs on life cycle of plants, including seed germination, growth, development, genotoxicity, chlorophyll content, and total pigments, and the signaling pathways that are activated for the development of defense mechanisms against the NPs.

10.2 Mechanisms of NBMs Phytotoxicity

Nano-based materials cause phytotoxicity through several mechanisms such as aggregation of NPs, release of metal ions, and oxidative stress (Thiruvengadam et al., 2024). Furthermore, a study carried out by Rajput et al. (2020b) revealed additional negative impacts of NPs, including reduced biomass, disruption of chlorophyll synthesis, decreased seed germination, modifications of the cellular and subcellular organelles ultrastructure, inhibition of photosynthesis, chromosomal aberrations, DNA damage, mitochondrial dysfunction, and inhibition of transcriptional and translational processes. NPs interact with pores in plant cell wall and

disrupt them, enter the cytoplasm *via* endocytosis, and interact directly with the different cell organelles, including endoplasmic reticulum (ER), chloroplasts, and mitochondria. In addition to interactions with the plant organelles and after passing through the nuclear membranes, these NPs interact directly with DNA and histones (Zafar et al., 2023). Through direct and indirect pathways, NPs can stimulate DNA damage. In the direct pathway and after entering the nucleus, NPs disrupt the DNA replication and transcription through interacting with it. Meanwhile, in the indirect pathway, an oxidative stress is induced by NPs leading to an oxidative burst, which stimulates the NPs entry into the nucleus, followed by a series of cellular events that cause destruction of the mitotic spindles and nuclear proteins, finally leading to apoptosis and DNA damage (Magdolenova et al., 2014). The reactive oxygen species (ROS) involve hydroxyl ($\cdot\text{OH}$) and superoxide ($\text{O}_2^{\cdot-}$) radicals, and singlet oxygen ($^1\text{O}_2$) and hydrogen peroxide (H_2O_2) as non-radical species. If triggered in an appropriate amount, these ROS are non-toxic; however, their over-production causes deleterious impacts in plants (Javed et al., 2024). NBMs cause phytotoxicity by releasing excessive amounts of ROS. These ROS can cause lipid peroxidation, alter the cell electric charge, bring about oxidative stress, damage the cell membranes, and break apart the damaging proteins peptide chains (Dhiman et al., 2021). Phytotoxicity is always associated with cytogenotoxicity. NPs cause phytotoxicity by destructing the mitochondrial electron transport chain (ETC) and impede the chloroplast photosystem I & II, affecting the processes of plant respiration and photosynthesis. Moreover, NPs damage the DNA, thereby leading to inactivation of cell cycle and encoded proteins, and impairment of mRNA synthesis. All these phenomena lead to plant cell death *via* impairment of the cells' normal functioning (Zafar et al., 2023). NPs cause plant cytotoxicity, genotoxicity, and phytotoxicity in the agricultural sector (Muzammil et al., 2023). With respect to food safety, NPs accumulation in the edible plant components represents a recognizable challenge (Thiruvengadam et al., 2024).

10.3 NBMs Uptake in Plants

Plants are exposed to several abiotic stresses such as aerosols and soil NBMs. NBMs uptake, translocation, and accumulation within the plant depend on their physico-chemical characteristics, including stability, concentration, surface chemistry, chemical configuration, and size, etc. NBMs may enter the plant leaves through two pathways; mainly stomatal and cuticular ones. As existing in the outermost waxy layer of the plant, cuticle protects the leaves from loss of water and regulates the exchange of solutes. Due to its unusual characteristics, cuticle is regarded as the earliest natural plant defense. Based on the kind of solutes, the cuticular pathway is further split into two major pathways: hydrophilic and lipophilic. The hydrophilic pathway involves uptake of polar solutes through polar aqueous pores with an efficacious size of 0.6–4.8 nm. Meanwhile, the lipophilic pathway includes the uptake of nonpolar solutes through permeation and diffusion (Azim et al., 2023).

For transportation of NBMs in higher plants, there are two major pathways such as apoplastic and symplastic ones. Singh et al. (2018) reported that during apoplastic pathway, translocation of NBMs as macromolecules may take place through epidermis, cortex, and endodermis. However, further translocation becomes restricted due to the existence of casparian strip in adjacent cells of the endodermis. For uptake of NBMs in plants, endocytosis is considered as a highly feasible pathway, while aquaporins act as non-endocytic pathways (Azim et al., 2023).

The uptake mechanisms of NBMs and interactions with the plants are essential aspects for understanding their influence on these plants. Plant NBMs uptake starts from the roots and extends to the upper parts, including stems, leaves, and flowers. This process is called the roots-shoots pathway, which is very complex. The NBMs enter plant cells through the cell wall and cytomembrane, and through simple sub-cells, including plasmodesmata and other channels from the plasmalemma to plasmodesmata, mitochondrion, nucleus, and chloroplast, etc. This transfer process is complex and some interactions are still unclear. Once NBMs enter plant cells; even in medium concentrations, they can generate ROS, which may spread from root to shoot, affecting plant growth, development, and metabolism (Liu et al., 2021).

Nanoparticles movement and delivery from the plant root to stem and leaves through the xylem and phloem tissues involves two pathways; mainly soil amendment and foliar spray (Du et al., 2017).

10.3.1 Root Uptake

Nanoparticles enter cells of root through cracks initiated during formation of lateral roots, and then through aquaporins, plasmodesmata, cell wall pores, ion transporters, and endocytosis (Khan et al., 2019b). In the study conducted by Yin et al. (2019), aquaporins have been defined as ion channels (1 nm in size) of plasma membrane that may allow entry of the NPs, thereby behaving as effective carriers for uptake of NPs through diffusion. To allow their entry into the root cells, NPs cause punctures in the root cell plasma membrane (Chichiriccò & Poma, 2015). Moreover, NPs may enter cells of root *via* endocytosis by engulfment and movement within the intracellular vesicles and then they invade the cell membrane. Furthermore, Khan et al. (2019b) added that carrier proteins or ion transporters may play an appreciable role in transport of NPs through cells of root. For transport of NPs across the cell membrane, endocytosis and non-endocytic mechanisms are regarded as recent pathways for their entry into the root. Gao et al. (2023) highlighted that NPs transport is influenced by their physical characteristics, including shape, size, and surface charge.

A study carried out by Pérez-de-Luque (2017) revealed that NPs' uptake and transport through the root involves three pathways; mainly soil amendment or foliar spray, use of symplastic and apoplastic channels for NPs movement, and internalization into the root cells.

For expedient absorption in the soil, NPs interact with organic matters, microorganisms, and salt ions. Several organic matters such as humic acids contribute to

NPs bioavailability in the soil (Cartwright et al., 2020). With respect to microorganisms, a study reported by Wang et al. (2016) that fungi and bacteria facilitate plants NP's uptake by making symbiotic relationships with these plants (*i.e.*, mycorrhizae). Recently, Biswas and Pal (2024) revealed that for movement within the plant tissues, NPs follow the apoplastic and symplastic pathways once they enter into the plant cells. NPs can move within the plant tissues using the apoplastic pathway that enables them to pass through the central cylinder of the root, and then they move towards the aboveground part *via* the xylem (Mittal et al., 2020). *Via* a symplastic pathway, the casparian strip is to be bypassed through cells of the endodermis (Lv et al., 2015); however, the casparian strips are not present in root tips, thereby NPs uptake through these strips is conducted through an apoplastic mode (Lv et al., 2019). Conversely, the symplastic mode allows movement of substances among adjacent root cells and through plasmodesmata, where this mode of transport provides allocations to the non-photosynthetic organs (Raliya et al., 2016). AgNPs aggregate on plasmodesmata and cell walls of root, causing block to the intercellular spaces within the root, thereby inhibiting or reducing nutrients translocation to the other cells (Geisler-Lee et al., 2014).

The study conducted by Biswas and Pal (2024) reported that during passage of NPs across the phloem, they may accumulate in several plant organs that act as sinks, including grains, leaves, flowers, and fruits. Nile et al. (2022) revealed that to comply with the symplastic mode of transfer, NPs must pass through plasma membrane by formation of pores (according to structure, size, charge, and hydrophobicity of NPs), carrier proteins (*i.e.*, across channels and trans-membrane proteins governing NPs transfer into the root cells), endocytosis, and ultimately they reach the cytosol. Absorption and transportation of NPs through the root is distorted by several plants' anatomical and physiological characteristics such as age, genotype, cuticle, dissimilarity of vascular bundles radii, exudates, trichomes, and root mucilage (Avellan et al., 2017).

10.3.2 Leaf Penetration

Upon entry of NPs into the leaves, they are passively absorbed *via* natural openings existing in plant leaves such as stomata and hydathodes (Khan & Ahmad, 2022). Later, Azim et al. (2023) added that cuticle and wounds act as portals for NPs entry into the plants. NPs foliar exposure may cause their entry through cuticle, stomata, trichomes, and lenticels, and then they move downwards *via* the phloem (Khan et al., 2019c). A study conducted by Ha et al. (2021) confirmed that stomata serve also as a main portal for absorption of NPs. Due to the existence of nano-sized pores in the leaf plasmodesmata, which support effective delivery of nutrients, diffusion of NPs *via* foliar spray is more promising than that *via* soil amendment (Javed et al., 2024). A study carried out by Ali et al. (2021) reported that cuticle protects the leaf, where NPs pass through this cuticle and ultimately reaching their target site. NPs may use either lipophilic or hydrophilic pathway for their entry. According to Hong et al. (2021), lipophilic diffusion takes place through cuticular waxes, while

hydrophilic uptake occurs through polar pores in the stomata and/or diffusion. Meanwhile, in the case of foliar exposure, endocytosis of NPs may also take place. Excessive foliar exposure to NPs induces heating effects on the leaves by impairing stomatal activities such as transpiration and gaseous exchange, leading to negative impacts on plant cell functions and physiology (Arruda et al., 2015).

10.4 Effect of NBMs on Plant Seed Germination, Growth, and Yield Parameters

Nanotechnology has proven to be useful in many different ways for biological advancement. For many grain and cash crops, for instance, nanotechnology devices are enhancing the growth of seed crops that have been treated with NBMs, boosting the yield, and enhancing the amount and quality of items produced. In the food and agricultural fields, nanotechnology is a rapidly emerging field that has produced a wide range of instruments and approaches for crop enhancement (Rashad et al., 2021). Recently, it has been thought that using nanomaterials to control plant pests, including fungi, insects, and weeds, would be an effective alternative to traditional control methods (Ghidan et al., 2019). Studying the impact of NBMs on plants seed germination holds a great promise in the agricultural practices field. During the life cycle of plants, seed germination is a crucial step, which represents the beginning of development and growth. Successful seeds germination is essential for crop production and overall plant health. Understanding how NBMs affect this process is important for assessing the benefits or risks of using nanotechnology in the sector of agriculture. Growth, germination, and acclimation of seeds are all regulated by the application of NPs. Applying multi-walled carbon nanotubes (MWCNT) on plants has increased biomass production and promoted seed germination in barley, wheat, maize, and garlic (Shang et al., 2019). Silicon dioxide (SiO_2) and Titanium dioxide (TiO_2) NPs have been shown to aid in seed germination in a variety of crops (Singh et al., 2015). Although recent studies have shown that NPs can penetrate the seed coat and facilitate nutrient and water absorption; however the precise mechanism of NPs-mediated seed germination remains unclear (Banerjee & Kole, 2016). In maize and cabbage, application of AgNPs has promoted root initiation (Pokhrel & Dubey, 2013). According to a study reported by Zheng et al. (2005), adding TiO_2 NPs to spinach has increased the plant's photosynthetic activity by increasing the amount of protein and chlorophyll. Similarly, the Rubisco enzyme is stimulated when TiO_2 NPs are applied to spinach. Au-NPs have a similar stimulating effect on plant height and leaf count, which is linked to increased crop productivity (Gopinath et al., 2014). Pearl millet's protein and chlorophyll levels have risen when green synthesized ZnNPs are applied, the shoot growth and productivity have also been improved (Song et al., 2012). *Ocimum basilicum* has benefited from the application of Fe_3O_4 NPs in terms of protein, carbs, chlorophyll, and essential oils (El-Feky et al., 2013).

In general, the effect of NBMs on seeds germination is a complicated matter. To completely comprehend the workings and create safe and advantageous uses of

nanotechnology in agriculture, more research studies are required. Szöllősi et al. (2020) study displayed that NBMs affect germination of seeds and growth of seedlings in two ways: positively and negatively. For example, it has been demonstrated that carbon NBMs, such as carbon nanotubes, C60, and graphene improve rice seed germination and growth (Nair et al., 2012). In a similar vein, it has been discovered that metal NPs like Fe and Cu promote the growth and development of Scotch pine seeds and seedlings (Polischuk et al., 2019). Conversely, several studies have shown that many types of NPs, including MWCNTs, TiO₂, Fe₂O₃ nanocubes, Fe₂O₃ long nanorods, and Fe₂O₃ short nanorods can impede the germination of rice seeds (Hojjat, 2016). These results emphasize the need for more investigations to pinpoint the precise processes and circumstances governing how NPs affect seed germination and seedling development.

Specifically, it has been demonstrated in a previous study that CuO-NPs cause phytotoxicity to different kinds of plants. At 0, 20, 50, 100, 200, and 500 mg/L, CuO-NPs have reduced the Indian mustard roots and shoots growth in a dose-dependent manner (Liu et al., 2018). In addition, CuO-NPs have slowed down maize growth (*i.e.*, height, fresh weight, and leaf surface area) at 500 mg/L (Sui et al., 2014). At doses more than 10 mg/L, CuO-NPs have remarkably hindered the growth of transgenic and normal cotton plants with respect to plant height, length of root, roots number, and biomass production (Le Van et al., 2016). Furthermore, at 10–100 mg/L, CuO-NPs have induced DNA damage in grassland and agricultural plants (*i.e.*, annual and perennial ryegrass, and radish) by causing 7,8-dihydro-8-oxoguanine (Atha et al., 2012). Notably, at target concentrations during various stages of rice growth, CuO-NPs have elicited a range of phytotoxicity in this plant. CuO-NPs have substantially reduced rice seedlings' root growth at 5 mg/L *via* producing ROS and altering the levels of expression of a pair of genes linked to root growth; mainly *OsCDC2* and *OsCYCD* (Wang et al., 2016). Furthermore, these CuO-NPs have caused oxidative damage to rice seedlings, reduced seed germination, and shoot and root growth at doses of 0.5, 1.0, and 1.5 mM (Shaw & Hossain, 2013). Plant biomass and length have been reduced after the tillering stage. On treatment with a high concentration of CuO-NPs (1000 mg/L), the plants at their heading stage have experienced fatal effects. The following is a summary of plausible NPs toxicity mechanisms: (1) alteration or damage to DNA (Wang et al., 2016), (2) production of ROS and causing oxidative stress (Wang et al., 2013), (3) NPs penetration into the cell interferes with the intracellular metabolism (Limbach et al., 2007), (4) metal ions released from NPs impede the activity of enzymes, and (5) NPs adsorbing on a plant organ's surface (*e.g.*, seed) produce locally concentrated ions (Tang et al., 2013). Numerous studies have demonstrated the successful use of Fe₂O₃-NPs as a nanofertilizer. Soil and foliar application of NPs could alleviate their negative impacts by enhancing chlorophyll content and Fe uptake, controlling phytohormone content and mechanisms of plant defense, increasing length of shoot and root, and increasing biomass of plants (Sun et al., 2024). Use of nano-metal oxides can considerably enhance nutrition of crop and productivity; however, various plant species have responded differently to the same

nanomaterial. In mung beans (*Vigna radiata*), Fe₃O₄-NPs have not exhibited any discernible phytotoxicity against this plant at a concentration of 1000 mg/L (Sun et al., 2020). On the other hand, Fe₃O₄-NPs have decreased *Cucurbita pepo* biomass, plant growth, and chlorophyll content (Tombuloglu et al., 2020). FeNPs may completely change the specific plant morphological and physiological processes, where this is a double-edged sword for development and growth of the plant (Sun et al., 2024).

The use of AgNPs has several benefits on root germination. AgNPs have the ability to combine with seed coats and aid in the uptake of water inside these seeds, hence accelerating the germination and metabolism of starch. In order to improve starch metabolism and rice-aged seeds, AgNPs are also used as a nano-priming agent. AgNPs work by controlling the expression of genes that encode aquaporins, which promote the diffusion of water and H₂O₂ to enhance the growth of seedlings. Nano priming is also linked to increasing α -amylase activity, which results in a larger concentration of soluble sugars (Khan et al., 2023). On applying AgNPs (1 mM) on bajra (*Pennisetum glaucum*) seeds, improvements in plumule and radicle length and improved seed germination have been noted within just 3 days (Sable et al., 2018). Additionally, at a concentration of 10 μ g/mL, AgNPs have successfully increased germination percentage of lentils, mean germination time of these plants, germination characteristics, and improved their tolerance under drought circumstances (Hojjat, 2016). A study reported by Wang et al. (2020) found that AgNPs are predominantly localized in cell walls and intercellular gaps after being absorbed by roots. Furthermore, when Arabidopsis plant is exposed to a concentration of 50 mg/L of AgNP, a dose-dependent effect on root growth and increased root elongation has been recorded. However, at 100 mg/L or more, a decrease in root elongation has been recognized (Tables 10.1 and 10.2).

10.5 Effect of NBMs on Chlorophyll Content and Total Pigments

Chlorophyll *a* and *b* are the main pigment classes found in plants, constituting the major light absorbers in leaves. Xanthophylls (*i.e.*, zeaxanthin, lutein, and violaxanthin) and carotenes (*i.e.* α - and β -carotene) are also found, protecting photosystems from excessive light and scavenge the ROS through their ability to quench chlorophyll triplet states and triplet oxygen generation in the presence of excess light (Singh et al., 2021). Pigments are important molecules for photosynthesis and antioxidant defense system in plants. Chlorophyll, the main photosynthetic pigment, plays a significant role in maximizing photosynthesis and enhancing growth of plants. The total pigments reflect growth, photo-oxidation, and other development aspects of plants (Simkin et al., 2022).

Table 10.1 Effect of nanoparticles on plant seed germination and growth parameters

NBMs	Target plants	Plant growth parameters	Reference
Si-NPs	Grapes, mango	Leaf surface area (+), shoot length (+), plant growth (+)	Rashad et al. (2021)
Ag-NP	Wheat	Seed germination and growth (+)	Iqbal et al. (2019)
ZnO-NP	Peanut, arabica coffee, soybean, mango,	Root growth (+), plant growth (+), rate of germination (+), dry weight (–)	Rossi et al. (2019) Singh et al. (2023)
CuO-NP	Spinach	Biomass (+)	Wang et al. (2019)
SiO ₂ -NP	Rice, straw-berry, bananas	Vegetative growth (+), shoot growth (+)	Mahmoud et al. (2020)
Fe ₂ O ₃ -NP	Mung bean, rapeseed	Biomass (+), leaf growth rate (+),	Palmqvist et al. (2017)
TiO ₂ -NP	Spinach, wheat	Biomass (+), growth (+), seedling dry weight	Shang et al. (2019)
Fe-NPS	Wheat	Growth (+)	Adrees et al. (2020)
Ag-NPs	Wheat, fenugreek	Germination rate (+), fresh and dry mass wheat (+), root and shoot length (+), root number (+), leaf area (+), fresh and dry mass (+)	Abou-Zeid and Ghada Ismail (2018), Iqbal et al. (2019)
Chitosan-NPs	Tomato	Growth (+)	Hernández-Hernández et al. (2018)
CeO-NPs	Cotton	Root parameters (+)	Preetha et al. (2023)
Fe ₃ O ₄ -NPs	Strawberry	Plantlets growth parameters (+)	Mozafari et al. (2018)
FeSO ₄ -NPS	Sunflower	Leaf area (+), shoot dry weight (+)	Torabian et al. (2018)
Fe ₂ O ₃ -NPs	Sunflower	Leaf area (+)	Moradbeygi et al. (2020)
Al ₂ O ₃ -NPs	Soybean	Hypocotyl length (+)	Mustafa and Komatsu (2016)
Cu-NPs	Corn	Biomass (+)	Nguyen et al. (2022)
Se-NPs	Tomato	Shoot fresh and dry weight (+), root fresh (+) and dry weight (+)	Haghighi et al. (2014)

Where; Positive (+), negative (–), and no impact (N)

Numerous studies revealed that lower concentrations of NBMs have a stimulatory effect on chlorophyll (*a* and *b*) contents and total chlorophyll, while higher concentrations decrease the amount of chlorophyll (Mahmoud et al., 2020). Chlorophyll production is catalyzed by NPs, which may also preserve the structure of chloroplasts (Shyam & Aery, 2012). Several previous studies reported that NBMs; even at low concentrations, can affect the amount of chlorophyll in plants. In this context, TiO₂ NPs have significantly suppressed the chlorophyll content. However, these declarations are inconsistent with the results reported by Bakshi and Kumar (2023) study (Table 10.3).

Table 10.2 Impact of nanoparticles on plant yield parameters

NMBs	Target plants	Plant yield parameters	References
Si-NPs	Grapevines	Yield/vine, Cluster weight, Size and weight of 100 berries, Cluster length and width, Berry diameter (mm) and length (+)	Rashad et al. (2021)
ZnO-NP	Peanut, wheat	Yield (+)	Du et al. (2019)
CuO-NP	Wheat	Yield (+)	Dimkpa et al. (2012)
Chitosan-NPs	Barley	Grain weight (+)	Behboudi et al. (2019)

Where; Positive (+), negative (–), and no impact (N)

Table 10.3 Effect of nanoparticles on chlorophyll content and total pigments

NBMs	Target plants	Chlorophyll content	Total pigments	References
Si-NPs	Grapevines	+	+	Rashad et al. (2021)
CeO-NPs	Arabidopsis		+	Preetha et al. (2023)
ZnO-NP	Peanut, okra	+	+	Abdallah and Alzahrani (2020)
TiO ₂ -NP	Spinach, chickpeas, wheat	+	+	Faraji and Sepehri (2020)
SiO ₂ -NPs	Strawberry, banana	+	+	Mahmoud et al. (2020)
Fe-NPs	Wheat	+	+	Adrees et al. (2020)
Chitosan-NPs	Tomato	+	+	Hernández-Hernández et al. (2018)
Cu-NPs	Corn	+	+	Nguyen et al. (2022)
Fe ₂ O ₃ -NPs	Rapeseed	+	+	Palmqvist et al. (2017)
FeSO ₄ -NPS	Sunflower	+		Torabian et al. (2018)

Where; Positive (+), negative (–), and no impact (N)

10.6 Defense of Plants Against NBMs

10.6.1 Oxidative Defense

Nano-based materials may impair plant membranes and impact plant defense system against free radicals (Ozyigit et al., 2016). After penetration and accumulation of NPs in tissues of plant, their primary mechanism of phytotoxicity involves induction of ROS production (Manna et al., 2022). Upon induction by NPs exposure, excessive ROS production causes lipid peroxidation, triggers an oxidative stress, changes structure of cell, causes damage to the biologically important DNA and proteins

macromolecules, and disrupts integrity of cell membrane, finally causing death of plant cell and inhibition of growth (de Medeiros et al., 2023). Upon facing NP's stress, plants trigger the antioxidant defense system and fight ROS accumulation *via* formation of hydrogen peroxide (H_2O_2) from superoxide radicals, followed by H_2O_2 splitting (Biswas & Pal, 2024). In a recent study, Hatami and Ghorbanpour (2024) reported that plant cell antioxidant defense may be divided into two main categories: (1) Enzymatic defense system, including enzymes that remove free radicals and other ROS types, and (2) Non-enzymatic defense system, involving antioxidants represented by several biological compounds of low molecular weights. Both groups work, either singly or in combination, to remove and/or reduce production of ROS in the cell (Nawaz et al., 2021). Induction of oxidative stress preceded by ROS production and accumulation in the plant cell disrupts functioning of several redox reactions and physiological processes within the cell. Overproduction of ROS causes some consequences in the cell, including DNA strand breaks, lipids peroxidation, mitochondrial damage, protein structure alteration, and final cell death. As a protective mechanism of the cell against the oxidative stress induced by exposure to NPs, the activities of several antioxidant enzymes increase (Singh et al., 2017). The main enzymatic antioxidants having ROS scavenging activity comprise peroxidase (POD), ascorbate peroxidase (APX), superoxide dismutase (SOD), catalase (CAT), and glutathione reductase (GR). Meanwhile, the non-enzymatic antioxidant system includes phenolics, ascorbate, carotenoids, alpha-tocopherol, glutathione, and flavonoids, which play a basic role in maintenance and detoxification of plant cell *via* reducing the ROS level and balancing the redox reactions (Hatami & Ghorbanpour, 2024). A previous study highlighted that enhancement of SOD enzyme is accompanied with enhancing the plants' tolerance against different environmental stresses such as NPs toxicity (Zhang et al., 2017). CAT enzyme exists in almost all living organisms and detoxifies ROS accumulating in the cell. In addition, CAT causes decomposition of H_2O_2 and decreases its deleterious impacts. APX uses ascorbate as a reducing agent or a potent antioxidant, and detoxifies H_2O_2 *via* its conversion into O_2 and H_2O . Hasanuzzaman et al. (2019) added that APX oxidizes ascorbate into monohydroascorbate (MDA) and has a role in ascorbate-glutathione pathway. Meanwhile, POD enzyme helps in breaking down H_2O_2 through oxidizing the phenolic compounds such as guaiacol (Hatami & Ghorbanpour, 2024).

Antioxidants are defined as molecules that prevent cell destruction and free radicals chain reactions through maintaining stability to these free radicals and providing them with electrons. Maintenance of cellular redox balance is based mainly on its antioxidant defense, which is a mechanism that helps to decrease the oxidative damage and acts as a redox buffer that maintains ROS physiological level required for signaling (Riaz et al., 2022). In presence of NPs and to protect the cellular components from oxidative damage, production and accumulation of carotenoids, phenols, phenolic acids, flavonoids, glutathione, and alkaloids takes place besides enzymes (Rezayian et al., 2023). In an attempt to discuss the role of NPs and their bulk counterparts in oxidative stress response and lipid peroxidation in treated plants, several experiments have been conducted on NPs treated and untreated

tomato plants to determine their MDA and H_2O_2 levels. Application of NPs/bulk counterparts on tomato plants has caused a noticeable oxidative stress response in terms of H_2O_2 and MDA levels, which have appreciably elevated in treated plants, compared to untreated ones (Malandrakis et al., 2021).

Recently, Pokharel et al. (2024) highlighted that in plants, lipid peroxidation triggers a defense response, including effective antioxidant enzymes and antioxidants of low molecular weight. In plants, this system acts as the primary defense mechanism *via* countering the ROS damage. According to Ahmed et al. (2017), all these defense components work, either singly or in combination, to decrease toxicity and oxidative damage induced by NPs. In a similar study carried out by Ahmed et al. (2018), the level of oxidative stress induced by treatment of tomato leaves, roots, and shoots with Al_2O_3 NPs has been assessed through estimating several antioxidant enzymes activity, including CAT, SOD, and Glutathione peroxidase (GPX). The obtained results demonstrated that NPs exposure has caused recognizable changes in functions of these antioxidant enzymes, through activating the plant cell's defense mechanism against the NPs induced stress.

10.6.2 Defense Through Secondary Metabolites Production

Plant metabolism has been divided into two main classes: (1) primary metabolism related to production of energy and building blocks, and (2) secondary metabolism that comprises metabolism of several secondary metabolites (Gowtham et al., 2024).

In contrast to primary metabolism, the secondary metabolism provides structurally different and specialized compounds, including organo-sulfur compounds (*i.e.*, glucosinolates), thioesters, phenylpropanoids (*i.e.*, stilbenes, polyphenols, anthocyanins, xanthenes, and flavonoids), prenylated phloroglucinols, terpenes, alkaloids, and polyketides (Selvakesavan et al., 2023). These compounds play vital roles in plant defense system against the abiotic stresses, and include antioxidants that control ROS, phytoalexins, chelators that scavenge free metal ions, growth regulators, phytoanticides and phytoncides (*i.e.*, represent defense against multiple biotic stresses), and UV protectants (Nobahar et al., 2021). Multiple studies have demonstrated the role of NBMs in improving the plants secondary metabolites. In a study reported by Kruszka et al. (2022), an untargeted metabolic trial has been employed to study the impact of several NBMs and NBMOs, including Au, Ag, Cu, ZnO, CuO, TiO_2 , and CeO_2 on *Hypericum perforatum* used as a cell broth culture. The obtained results have revealed that NBMs enhanced the production of secondary metabolites higher than NBMOs. Meanwhile, Ag and CuO NPs in particular have induced considerable changes in plants secondary metabolism. These results have displayed that elicitation of plants secondary metabolites varies among the various types NBMs. Shang et al. (2019) highlighted that the ability of plants to adapt to various abiotic stresses such as NPs pollution, has been manifested by complex interrelated reactions controlled by signaling molecules and phytohormones.

Upon exposure to NPs stress, plants may be stimulated to synthesize large amounts of various secondary compounds through the JA-mediated pathways, including phenolics, alkaloids, and terpenes, where all are considered as effective mechanisms of plant defense (Takshak & Agrawal, 2019). Development of these secondary metabolites demonstrates that JA pathway may go beyond its classical functions and can shape the plant responses to NPs stress (Pereira et al., 2021). Similarly, SA signaling pathway is also able to treat against hazards of nanopollution (Anand et al., 2008). Later, Andersson-Willman et al. (2012) revealed that plants immune system can mobilize SA signaling upon internalization of NPs into their ecosystem. NPs pollution induces plants to produce ethylene, leading to the development of several reactions with ramifications in multiple plant biology areas (Gayathiri et al., 2024). When plants are exposed to NPs stress, ethylene alters the relationship between plants and microorganisms, improving tolerance to stress, plant resilience, and absorption of nutrients (Rasheed et al., 2022). This achieved coordination caused by EA-mediated signaling expresses the plant responses complexity to NPs pollution. Due to complex actions of the signaling molecules and phytohormones, plants create complicated ways to treat this novel problem of NPs stress (Gayathiri et al., 2024).

10.7 Effect of NBMs on Treated Plant Ultrastructure

Several studies have indicated clear damages to plant cell organelles treated with NPs, including mitochondria, thylakoids, plastoglobules, peroxisomes, protoplasm, starch granules, plastids, protoplasm, plasma membrane vascular bundles, epidermis, cell wall, morphology of root, central cylinder, morphology, vascular bundles, and endodermis (Rajput et al., 2018a). In the study conducted by Kouhi et al. (2015), cross sections of ZnO-NPs and ZnO bulk particles treated root cells have demonstrated a decrease in diameter of root tips in the treated plants compared to the control, while bulk particles have caused a decrease in size of cortical cells of epidermis; however, both treatments have affected the pericycle and stellar cells. Rajput et al. (2018b) have recorded disturbances in epidermis and integrity of endodermal cell wall, disorganization and vacuolization of endoplasmic reticulum (ER), and destruction of mitochondrial cristae and its swellings in *Hordeum sativum distichum* roots treated with CuO-NPs at elevated concentrations. Similarly, AgNPs have induced a destroy and vacuolization in nuclei of *Nicotiana tabacum* (Cvjetko et al., 2018), deteriorated mitochondrial cristae and abundance of peroxisomes in NiO-NPs treated *Lycopersicon esculentum* (Faisal et al., 2013), and increased metaxylem counts in AgNPs treated *Zea mays* (Pokhrel & Dubey, 2013). These destructive changes in organelles structure and ultrastructure are associated with impaired performance and plant growth (Rajput et al., 2020a). In the study reported by Labeeb et al. (2022), high concentrations of AgNPs have caused the root cells to become degraded and highly plasmolyzed. Similarly, Hasan et al. (2021) obtained results have recorded that AgNPs (10 µg/mL) caused cell death on lettuce.

Moreover, the results obtained in the chloroplast have displayed an increase in number of starch grains on treatment with AgNPs at a low concentration of 20 mg/L. This increase in number of starch grains in the leaf cells may be attributed to stimulated starch accumulation and an increase in the photosynthetic machinery as defense mechanisms against AgNPs (Aleksandrowicz-Trzcinska et al., 2019). After seed priming with high concentrations of AgNPs, the broad bean seedlings have displayed less stacking of grana and irregular shape of the chloroplasts accompanied with protrusions (Abdel-Aziz & Rizwan, 2019). Meanwhile, according to Fayez et al. (2017), destruction of the mitochondrial structure is regarded as a physiological dysfunction that may affect the respiratory chain, thereby leading to the production of ROS. Grzelaka et al. (2018) highlighted that leakage of ROS and mitochondrial damage is the proposed mechanism of AgNPs toxicity. Alkhatib et al. (2019) revealed that tobacco (*Nicotiana tabacum*) plants treated with Fe₃O₄-NPs (5 nm) in all tested concentrations have shown impaired shape of cells, deformed cells of epidermis, reduced number of cortical cells, and thickened xylem cell walls, suggesting that Fe₃O₄-NPs are highly toxic. Furthermore, TEM-micrographs demonstrated that Fe₃O₄-NPs treated plants have shown an increment of vacuolation in the root cortex. Cross-sections of tobacco leaves treated with Fe₃O₄-NPs at 30 mg/L have displayed little deformation of the spongy parenchyma cells. Ultrastructural organization of leaf chloroplasts in tobacco plants treated with Fe₃O₄-NPs (5 nm) in all tested concentrations has expressed deformed chloroplasts of different shapes, indicating that Fe₃O₄-NPs toxicity has increased with increasing their corresponding concentration, leading to deformation in plants growth.

10.8 Molecular Phytotoxic Alterations Induced by NBMs

Gowtham et al. (2024) revealed that at elevated concentrations, NPs induce toxicity in plants at the molecular level. To induce genotoxic impacts in the plants such as DNA damage, reduction of mitotic index, formation of micronuclei, and increasing chromosomal aberrations, NPs interact with different biological macromolecules inside the cell, including nucleus, lipids, and cytoplasmic components (Manna et al., 2022). At high concentrations, NPs can enter cells of the root tips. Once being internalized, they express toxicity *via* inducing membrane integrity loss, break DNA strand, increase chromosomal alterations (*i.e.*, chromosomal stickiness, breakage, bridges, fragmentation, gaps, lagging, and disturbed chromosomes at the anaphase and metaphase), induce micronucleus formation, cause cell cycle arrest, and disrupt the normal cell functioning (Abdelsalam et al., 2018).

In a study conducted by Labeed et al. (2022), using inter-simple sequence repeats (ISSR) markers fingerprinting, the effect of AgNPs on pea seedlings genome's stability has demonstrated a polymorphism between the control and tested treatments; especially following treatment with AgNPs at concentrations of 20 mg/L and 40 mg/L. This obtained polymorphism may be attributed to the presence and/or absence of DNA loci between the samples, resulting from DNA damage ascribed to

point mutations, which are induced by AgNPs interaction with phosphorus of DNA (Li et al., 2013). Similarly, Bello-Bello et al. (2018) highlighted that exposure to AgNPs increases the ISSR polymorphism that may be useful in promoting the *Vanilla planifolia* genetic variability. These changes in ISSR profiles may be assigned to the increase in ROS that enhances damages of the genomic DNA through point mutations induction, leading to ISSR polymorphism. AgNPs induced variation in ISSR markers fingerprinting has revealed an increase in polymorphism caused by increasing AgNPs concentration (Labeeb et al., 2022). For ISSR markers, the majority of applied AgNPs have caused a noticeable effect; mainly band loss associated with unrepaired DNA damage, hindering amplification of sampled sites and developing point mutations at the annealing site (Sukumaran & Grant, 2013).

In the recent study reported by Pokharel et al. (2024) and in plants treated with $\text{Al}_2\text{O}_3\text{NPs}$, genetic toxicity; mainly DNA damage and aberrant expression of the coding and non-coding genes have been recorded. $\text{Al}_2\text{O}_3\text{NPs}$ have caused aberrant expression of microRNAs (miRNAs) (Burklew et al., 2012). miRNAs play significant roles in all biological and metabolic processes in plants, including response to different abiotic stresses such as NPs (Zhang et al., 2015), plant development (Li & Zhang, 2016), and change from vegetative to reproductive growth phase (Zhang et al., 2015). The miRNAs act by directing the messenger RNAs (mRNAs) to break down and/or inhibit the process of translation (Pokharel et al., 2024). A study conducted by Burklew et al. (2012) on tobacco seedlings has investigated the effect of $\text{Al}_2\text{O}_3\text{NPs}$ exposure on expression profiles of miRNAs. The obtained results have revealed that at 1% $\text{Al}_2\text{O}_3\text{NPs}$, expressions of different miRNAs; mainly *miR 159*, *miR 162*, *miR 167*, *miR 169*, *miR395*, *miR 396*, *miR397*, *miR398*, and *miR399* are upregulated. Meanwhile, at a lower tested concentration (0.1%), miRNAs expressions have been down-regulated. The obtained results of upregulation of miRNAs have displayed that these miRNAs may play a main role in regulating the stress response that has occurred in tobacco plants upon exposure to $\text{Al}_2\text{O}_3\text{NPs}$. Meanwhile, down-regulation of miRNAs can be attributed to different plant pathways that are induced in response to the stress developed on treatment with $\text{Al}_2\text{O}_3\text{NPs}$.

In *Arabidopsis thaliana* plants, ZnO-NPs cytotoxicity has been ascribed to a decrease in the expression of several photosystem structural genes, including *PSAK*, *PSAD2*, *PSAN*, and *PSAE2*, in addition to chlorophyll synthesis genes; mainly *CRD1*, *CAO*, *CHLG*, *CHLM*, and *CHLD*, which collectively have inhibited chlorophyll biosynthesis, causing a decrease in plant's photosynthetic efficiency (Wang et al., 2016). Similarly, at 100–200 mg/L, CuNPs application in *Capsicum annuum* has reduced the Mevalonate kinase (*MVK*) gene expression that acts in the terpenoid metabolism, leading to limitation in photosynthesis and decreasing efficacy of energy production, thereby reducing transcription in this plant (Tabatabaee et al., 2021). Treatment of *Taraxacum officinale* with CuO-NPs at 200 mg/L and ZnO-NPs at 100 mg/L has caused DNA damage, ascribed to NPs uptake through the leaves following the formation of complexes with the organic compounds and their dissociation as ions, and also induced an oxidative stress (Abrica-González et al., 2023).

10.9 Genotoxicity of NBMs

Plants are a significant route for NBMs bioaccumulation in food chain. The cell wall of plants has pores of 5–20 nm in diameters that act as a sieve. This permits NBMs smaller than a pore diameter to enter the plant *via* cell wall with ease (Kanakari & Dendrinou-Samara, 2023). NBMs are released into environment and accumulate at different nutritional levels. Plants can absorb NBMs and are extremely sensitive to nanotoxicity (Ghosh et al., 2019). Therefore, plants are thought to be exceptional genetic models for sorting and tracking of hazardous substances in the environment (Iqbal, 2016). To induce genotoxic and cytotoxic effects in plants such as raising micronucleus and chromosomes aberration index and lowering mitotic index, NBMs may interact with several bio-macromolecules, including lipids, nucleus, or cytoplasmic components (Youssef & Elamawi, 2020).

Rashad et al. (2021) observed that treatment of onion root tips with 100 µg/mL of SiNPs has shown a considerable increase in mitotic index, but those treated with SiNPs at 150 µg/mL have not displayed discernible changes in this parameter, compared to the control treatment. Nonetheless, for both treatments; a variety of anomalies have been observed during the interphase and at various stages of mitosis. Furthermore, after being exposed to SiNPs, the onion root tips have demonstrated a remarkable overall mitotic irregularity, with recorded percentages of 23.4% and 29.1% for treatments at 100 and 150 µg/mL, respectively. In the meantime, the electron microscope (EM) studies have revealed a variety of nuclear anomalies such as chromosomal stickiness in response to SiNP treatment at 150 µg/mL in all mitotic phases (Fig. 10.1). The impacts of AgNPs on wheat cell division and chromosomal aberrations have been assessed by Abdelsalam et al. (2018). They reported that cells of treated root tips have expressed a variety of chromosomal aberrations, including multicore, spindle dysfunction, incorrect orientation at metaphase, chromosomes breakage and lagging, and metaphase plate deformation. This suggests that cells of wheat root tips have been internalized by AgNPs with ease, and these NPs may have interfered with normal cell functions by preventing DNA synthesis in S phase.

After analyzing the cytogenetic effects of Cr₂O₃-NPs on onion root cells, it has been noticed that there is a considerable drop in mitotic index; additionally, there are chromosomal abnormalities at various exposure levels (Gao et al., 2023). Prior studies have shown that internalization of Cr₂O₃-NPs enhanced SOD production in response to oxidative stress, resulting in the recorded damage in DNA (Gao et al., 2023). Exposure to polystyrene NPs (PSNPs) has substantially decreased onion's mitotic index, caused various chromosomal aberrations (such as lagging or aggregating chromosomes), and induced spindle deformation, in addition, nuclear abnormalities have been noted. These events have disrupted the genome's stability and expressed genotoxicity caused by PSNPs exposure (Gao et al., 2023).

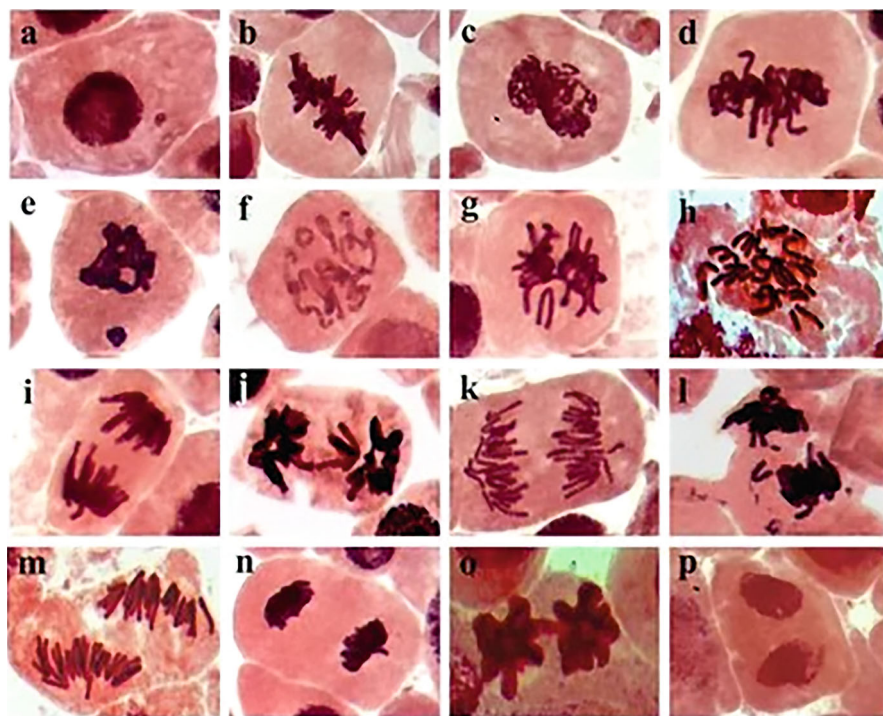


Fig. 10.1 Light micrographs depicted by Rashad et al. (2021) demonstrating aberrant mitosis in *Allium cepa* root tips following a 24-h treatment with SiNPs at 150 $\mu\text{g/mL}$. There observed; (a) micronucleus at interphase, (b) oblique at metaphase, (c) stickiness at metaphase, (d) disturbance at metaphase, (e) micronucleus at metaphase, (f) ring at metaphase, (g) non-congressing at metaphase, (h) polyploidy at anaphase, (i) late separation at anaphase, (j) bridge at metaphase, (k) disturbance at anaphase, (l) laggard at anaphase, (m) diagonal at anaphase, (n) disturbance at telophase, (o) bridge at telophase, and (p) diagonal at telophase

10.10 Conclusion

Nano-based materials have several beneficial uses to human. However, in the agricultural sector, their excessive use at elevated concentrations induces phytotoxicity, leading to high economic losses in crop production. NBMs induce phytotoxicity *via* several mechanisms, including NBMs aggregation, release of metal ions, and oxidative stresses. Uptake of NBMs through plants starts from roots and extends to the upper aerial parts such as stems, leaves, and flowers. They induce positive and/or negative effects on germination of seeds. NBMs may change and regulate the distribution of pigments in the plant photosystem through some related signaling factors. NPs exposure induces ROS production, which triggers an oxidative stress inside plants, causes lipid peroxidation, elicits direct damage to the important bio-macromolecules such as proteins and DNA, and finally leads to plant

cell death followed by inhibition of growth. Upon exposure to NPs, plants may be stimulated to synthesize large amounts of different secondary metabolites through the JA-mediated pathway, including phenolics, alkaloids, and terpenes, acting as effective plant defense mechanisms. NPs interact with different bio-macromolecules inside the cell, including cytoplasmic components, nucleus, and lipids, thus inducing genotoxic impacts in the plants such as DNA damage, reduction of mitotic index, formation of micronuclei, and increasing chromosomal aberrations. Finally, we concluded that NBMs can be applied effectively on a wide scale in the crop fields for control of biotic and abiotic stresses when manipulated at optimum non-phytotoxic concentrations and at scheduled rates, which are not deleterious to the plant or the environment.

References

- Abdallah, N. M., & Alzahrani, S. H. (2020). The potential mitigation effect of ZnO nanoparticles on (*Abelmoschus esculentus* L. Moench) metabolism under salt stress conditions. *Saudi Journal of Biological Sciences*, 27, 3132–3137. <https://doi.org/10.1016/j.sjbs.2020.08.005>
- Abdel-Aziz, H. M. M., & Rizwan, M. (2019). Chemically synthesized silver nanoparticles induced physio-chemical and chloroplast ultrastructural changes in broad bean seedlings. *Chemosphere*, 235, 1066–1172. <https://doi.org/10.1016/j.chemosphere.2019.07.035>
- Abdelsalam, N. R., Abdel-Megeed, A., Ali, H. M., Salem, M. Z. M., Al-Hayali, M. F. A., & Elshikh, M. S. (2018). Genotoxicity effects of silver nanoparticles on wheat (*Triticum aestivum* L.) root tip cells. *Ecotoxicology and Environmental Safety*, 155, 76–85. <https://doi.org/10.1016/j.ecoenv.2018.02.069>
- Abou-Zeid, H., & Ghada Ismail, G. (2018). The role of priming with biosynthesized silver nanoparticles in the response of *Triticum aestivum* L to salt stress. *Egyptian Journal of Botany*, 58, 73–85. <https://doi.org/10.21608/EJBO.2017.1873.1128>
- Ablica-González, P., Gómez-Arroyo, S., Jazcilevich-Diamant, A., Sotelo-López, A., Flores-Márquez, A. R., & Cort'es-Eslava, J. (2023). Evaluation of toxicological effects of ZnO and CuO nanoparticles with *Taraxacum officinale* as bioindicator. *Water, Air, and Soil Pollution*, 234, 443. <https://doi.org/10.1007/s11270-023-06432-3>
- Adrees, M., Khan, Z. S., Ali, S., Hafeez, M., Khalid, S., Rehman, M. Z. U., Hussain, A., Hussain, K., Chatha, S. A. S., & Rizwan, M. (2020). Simultaneous mitigation of cadmium and drought stress in wheat by soil application of iron nanoparticles. *Chemosphere*, 238, 124681. <https://doi.org/10.1016/j.chemosphere>
- Ahmed, B., Dwivedi, S., Abdin, M. Z., Azam, A., Al-Shaeri, M., Khan, M. S., et al. (2017). Mitochondrial and chromosomal damage induced by oxidative stress in Zn²⁺ ions, ZnO-bulk and ZnO-NPs treated *Allium cepa* roots. *Scientific Reports*, 7(1), 40685. <https://doi.org/10.1038/srep40685>
- Ahmed, B., Khan, M. S., & Musarrat, J. (2018). Toxicity assessment of metal oxide nano-pollutants on tomato (*solanum lycopersicon*): A study on growth dynamics and plant cell death. *Environmental Pollution*, 240, 802–816. <https://doi.org/10.1016/j.envpol.2018.05.015>
- Aleksandrowicz-Trzcina-ska, M., Bederska-Błaszczek, M., Szaniawski, A., Olchowik, J., & Studnicki, M. (2019). The effects of copper and silver nanoparticles on container-grown scots pine (*Pinus sylvestris* L.) and pedunculate oak (*Quercus robur* L.) seedlings. *Forests*, 10(3), 269. <https://doi.org/10.3832/for2855-011>
- Ali, S., Mehmood, A., & Khan, N. (2021). Uptake, translocation, and consequences of nanomaterials on plant growth and stress adaptation. *Journal of Nanomaterials*, 1–17. <https://doi.org/10.1155/2021/6677616>

- Alimi, O. S., Farner Budarz, J., Hernandez, L. M., & Tufenkji, N. (2018). Microplastics and nanoplastics in aquatic environments: Aggregation, deposition, and enhanced contaminant transport. *Environmental Science & Technology*, 4(52), 1704–1724. <https://doi.org/10.1021/acs.est.7b05559>
- Alkhatib, R., Alkhatib, B., Abdo, N., Al-Eitan, L., & Creamer, R. (2019). Physio-biochemical and ultrastructural impact of (Fe₃O₄) nanoparticles on tobacco. *BMC Plant Biology*, 19, 253. <https://doi.org/10.1186/s12870-019-1864-1>
- Ameh, T., & Sayes, C. M. (2019). The potential exposure and hazards of copper nanoparticles: A review. *Environmental Toxicology and Pharmacology*, 71, 103220. <https://doi.org/10.1016/j.etap.2019.103220>
- Anand, A., Uppalapati, S. R., Ryu, M., Allen, S. N., Kang, L., Tang, Y., & Mysore, K. S. (2008). Salicylic acid and systemic acquired resistance play a role in attenuating crown gall disease caused by *Agrobacterium tumefaciens*. *Plant Physiol*, 146(2), 703–715. <https://doi.org/10.1104/PP.107.111302>
- Andersson-Willman, B., Gehrmann, U., Cansu, Z., Buerki-Thurnherr, T., Krug, H. F., Gabrielsson, S., & Scheynius, A. (2012). Effects of subtoxic concentrations of TiO₂ and ZnO nanoparticles on human lymphocytes, dendritic cells and exosome production. *Toxicology and Applied Pharmacology*, 264, 94–103. <https://doi.org/10.1016/j.taap.2012.07.021>
- Arruda, S. C. C., Silva, A. L. D., Galazzi, R. M., Azevedo, R. A., & Arruda, M. A. Z. (2015). Nanoparticles applied to plant science: A review. *Talanta*, 131, 693–705. <https://doi.org/10.1007/978-3-662-66226-1>
- Atha, D. H., Wang, H., Petersen, E. J., Cleveland, D., Holbrook, R. D., Jaruga, P., Dizdaroglu, M., Xing, B., & Nelson, B. C. (2012). Copper oxide nanoparticle mediated DNA damage in terrestrial plant models. *Environmental Science & Technology*, 46, 1819–1827.
- Avellan, A., Schwab, F., Masion, A., Chaurand, P., Borschneck, D., Vidal, V., Rose, J., Santaella, C., & Levard, C. (2017). Nanoparticle uptake in plants: Gold nanomaterial localized in roots of *Arabidopsis thaliana* by X-ray computed nanotomography and hyperspectral imaging. *Environmental Science & Technology*, 51, 8682–8691. <https://doi.org/10.1021/acs.est.7b01133>
- Azim, Z., Singh, N. B., Singh, A., Amist, N., Khare, S., Yadav, R. K., Bano, C., & Yadav, V. (2023). A review summarizing uptake, translocation and accumulation of nanoparticles within the plants: Current status and future prospectus. *Journal of Plant Biochemistry and Biotechnology*, 32, 211–224. <https://doi.org/10.1007/s13562-022-00800-6>
- Bakshi, M., & Kumar, S. (2023). Investigating impacts of nanosized titanium dioxide (Nano-TiO₂) on maize (*Zea mays* L.) and their ensuing implications on soil physiochemistry: A soil exposure water. *Water, Air, and Soil Pollution*, 234, 559. [10.1007/s11270-023-06556-6](https://doi.org/10.1007/s11270-023-06556-6)
- Banerjee, J., & Kole, C. (2016). Plant nanotechnology: An overview on concepts, strategies, and tools. In C. Kole, D. Kumar, & M. Khodakovskaya (Eds.), *Plant nanotechnology* (pp. 1–14). Springer.
- Behboudi, F., Tahmasebi-Sarvestani, Z., Kassae, M. Z., Modarres-Sanavy, S. A. M., Sorooshzadeh, A., & Mokhtassi-Bidgoli, A. (2019). Evaluation of chitosan nanoparticles effects with two application methods on wheat under drought stress. *Journal of Plant Nutrition*, 42(13), 1439–1451. <https://doi.org/10.1080/01904167.2019.1617308>
- Bello-Bello, J. J., Spinoso-Castillo, J., Arano-Avalos, S., Martinez-Estrada, E., Arellano Garcia, M. E., Pestryakov, A., Toledano-Magana, Y., Garcia-Ramos, J. C., & Bogdanchikova, N. (2018). Cytotoxic, genotoxic, and polymorphism effects on *Vanilla planifolia* Jacks ex Andrews after long-term exposure to argovit® silver nanoparticles. *Nanomaterials*, 8, 754. <https://doi.org/10.3390/nano8100754>
- Biswas, A., & Pal, S. (2024). Plant-nano interactions: A new insight of nano-phytotoxicity. *Plant Physiology and Biochemistry*, 210, 108646. <https://doi.org/10.1016/j.plaphy.2024.108646>
- Burklew, C. E., Ashlock, J., Winfrey, W. B., & Zhang, B. (2012). Effects of aluminum oxide nanoparticles on the growth, development, and microRNA expression of tobacco (*Nicotiana tabacum*). *PLoS One*, 7(5), e34783. <https://doi.org/10.1371/journal.pone.0034783>

- Cartwright, A., Jackson, K., Morgan, C., Anderson, A., & Britt, D. W. (2020). A review of metal and metal-oxide nanoparticle coating technologies to inhibit agglomeration and increase bioactivity for agricultural applications. *Agronomy*, 10, 1018. <https://doi.org/10.3390/agronomy10071018>
- Chichiricò, G., & Poma, A. (2015). Penetration and toxicity of nanomaterials in higher plants. *Nanomaterials*, 5(2), 851–873. <https://doi.org/10.3390/nano5020851>
- Cvjetko, P., Zovko, M., Štefanić, P. P., Biba, R., Tkalec, M., Domijan, A. M., Vrček, I. V., Letofsky-Papst, I., Šikić, S., & Balen, B. (2018). Phytotoxic effects of silver nanoparticles in tobacco plants. *Environmental Science and Pollution Research International*, 25(6), 5590–5602. <https://doi.org/10.1007/s11356-017-0928-8>
- de Medeiros, R. L. S., de Paula, R. C., de Souza, J. V. O., & Fernandes, J. P. P. (2023). Abiotic stress on seed germination and plant growth of *Zeyheria tuberculosa*. *Journal of Forest Research*, 34, 1511–1522. <https://doi.org/10.1007/s11676-023-01608-3>
- Dhiman, S., Bakshi, P., Kapoor, N., Sharma, P., Kohli, S. K., Mir, B. A., & Bhardwaj, R. (2021). Nanoparticle-induced oxidative stress in plant. In *Plant responses to nanomaterials: recent interventions, and physiological and biochemical responses* (Nanotechnology in the life sciences) (pp. 269–313). https://doi.org/10.1007/978-3-030-36740-4_12
- Dimkpa, C. O., McLean, J. E., Latta, D. E., Manangón, E., Britt, D. W., Johnson, W. P., Boyanov, M. I., & Anderson, A. J. (2012). CuO and ZnO nanoparticles: Phytotoxicity, metal speciation, and induction of oxidative stress in sand-grown wheat. *Journal of Nano Research*, 14, 1–15. <https://doi.org/10.1007/s11051-012-1125-9>
- Du, W., Tan, W., Peralta-Videa, J. R., Gardea-Torresdey, J. L., Ji, R., Yin, Y., & Guo, H. (2017). Interaction of metal oxide nanoparticles with higher terrestrial plants: Physiological and biochemical aspects. *Plant Physiology and Biochemistry*, 110, 210–225. <https://doi.org/10.1016/j.plaphy.2016.04.024>
- Du, W., Yang, J., Peng, Q., Liang, X., & Mao, H. (2019). Comparison study of zinc nanoparticles and zinc sulphate on wheat growth: From toxicity and zinc biofortification. *Chemosphere*, 227, 109–116. <https://doi.org/10.1016/j.chemosphere.2019.03.168>
- El-Feky, S. A., Mohammed, M. A., Khater, M. S., Osman, Y. A., & Elsherbini, E. (2013). Effect of magnetite nanofertilizer on growth and yield of *Ocimum basilicum* L. *International Journal of Indigenous Medicinal Plants*, 46, 1286–1293.
- Faisal, M., Saquib, Q., Alatar, A. A., Al-Khedhairi, A. A., Hegazy, A. K., & Musarrat, J. (2013). Phytotoxic hazards of NiO-nanoparticles in tomato: A study on mechanism of cell death. *Journal of Hazardous Materials*, 250, 318–332.
- Faraji, J., & Sepehri, A. (2020). Exogenous nitric oxide improves the protective effects of TiO₂ nanoparticles on growth, antioxidant system, and photosynthetic performance of wheat seedlings under drought stress. *Journal of Soil Science and Plant Nutrition*, 20, 703–714. <https://doi.org/10.1007/s42729-019-00158-0>
- Fayez, K. A., El-Deeb, B. A., & Mostafa, N. Y. (2017). Toxicity of biosynthetic silver nanoparticles on the growth, cell ultrastructure and physiological activities of barley plant. *Acta Physiologiae Plantarum*, 39, 155. <https://doi.org/10.1007/s11738-017-2452-3>
- Gao, M., Chang, J., Wang, Z., Zhang, H., & Wang, T. (2023). Advances in transport and toxicity of nanoparticles in plants. *Journal of Nanobiotechnology*, 21, 75. <https://doi.org/10.1186/s12951-023-01830-5>
- Gayathiri, E., Prakash, P., Pandiaraj, S., Ramasubburayan, R., Gaur, A., Sekar, M., Viswanathan, D., & Govindasamy, R. (2024). Investigating the ecological implications of nanomaterials: Unveiling plants' notable responses to nano-pollution. *Plant Physiology and Biochemistry*, 206, 108261. <https://doi.org/10.1016/j.plaphy.2023.108261>
- Geisler-Lee, J., Brooks, M., Gerfen, J. R., Wang, Q., Fotis, C., Sparer, A., Ma, X., Berg, R. H., & Geisler, M. (2014). Reproductive toxicity and life history study of silver nanoparticle effect, uptake and transport in *Arabidopsis thaliana*. *Nanomaterials*, 4, 301–318. <https://doi.org/10.3390/nano4020301>

- Ghidan, W. F., El-Agoury, R. Y., & Hussein, F. A. (2019). Utilization of combining ability & genetic components for yield & its contributing traits of some rice (*Oryza sativa* L.) genotypes. *Journal of Agricultural Chemistry and Biotechnology*, 10(12), 257–267.
- Ghosh, M., Ghosh, I., Godderis, L., Hoet, P., & Mukherjee, A. (2019). Genotoxicity of engineered nanoparticles in higher plants. *Mutation Research*, 842, 132–145. <https://doi.org/10.1016/j.mrgentox.2019.01.002>
- Gopinath, K., Gowri, S., Karthika, V., & Arumugam, A. (2014). Green synthesis of gold nanoparticles from fruit extract of *Terminalia arjuna*, for the enhanced seed germination activity of *Gloriosa superba*. *Journal of Nanostructure in Chemistry*, 4, 1–11. <https://doi.org/10.1007/s40097-014-0115-0>
- Gowtham, H. G., Shilpa, N., Singh, S. B., Aiyaz, M., Abhilash, M. R., Nataraj, K., Amruthesh, K. N., Ansari, M. A., Alomary, M. N., & Murali, M. (2024). Toxicological effects of nanoparticles in plants: Mechanisms involved at morphological, physiological, biochemical and molecular levels. *Plant Physiology and Biochemistry*, 210, 108604. <https://doi.org/10.1016/j.plaphy.2024.108604>
- Grzelaka, A., Wojewodzka, M., Meczynska-Wielgosz, S., Zuberek, M., Wojciechowska, D., & Kruszewski, M. (2018). Crucial role of chelatable iron in silver nanoparticles induced DNA damage and cytotoxicity. *Redox Biology*, 15, 435–440. <https://doi.org/10.1016/j.redox.2018.01.006>
- Ha, N., Seo, E., Kim, S., & Lee, S. J. (2021). Adsorption of nanoparticles suspended in a drop on a leaf surface of *Perilla frutescens* and their infiltration through stomatal pathway. *Scientific Reports*, 11(11), 11556. <https://doi.org/10.1038/s41598-021-91073-x>
- Haghighi, M., Abolghasemi, R., & da Silva, J. A. T. (2014). Low and high temperature stress affect the growth characteristics of tomato in hydroponic culture with se and nano-se amendment. *Scientia Horticulturae*, 178, 231–240. <https://doi.org/10.1016/j.scienta.2014.09.006>
- Hasan, M., Mehmood, K., Mustafa, G., et al. (2021). Phytotoxic evaluation of phytosynthesized silver nanoparticles on lettuce. *Coatings*, 11(225), 1–14. <https://doi.org/10.3390/coatings11020225>
- Hasanuzzaman, M., Bhuyan, M. H. M. B., Anee, T. I., Parvin, K., Nahar, K., Mahmud, J. A., & Fujita, M. (2019). Regulation of ascorbate-glutathione pathway in mitigating oxidative damage in plants under abiotic stress. *Antioxidants*, 8(9), 384. <https://doi.org/10.3390/antiox8090384>
- Hatami, M., & Ghorbanpour, M. (2024). Metal and metal oxide nanoparticles-induced reactive oxygen species: Phytotoxicity and detoxification mechanisms in plant cell. *Plant Physiology and Biochemistry*, 213, 108847. <https://doi.org/10.1016/j.plaphy.2024.108847>
- Hernández-Hernández, H., González-Morales, S., Benavides-Mendoza, A., Ortega-Ortiz, H., Cadenas-Pliego, G., & Juárez-Maldonado, A. (2018). Effects of chitosan-PVA and Cu nanoparticles on the growth and antioxidant capacity of tomato under saline stress. *Molecules*, 23, 178. <https://doi.org/10.3390/molecules23010178>
- Hojjat, S. S. (2016). The effect of silver nanoparticle on lentil seed germination under drought stress. *International Journal of Farming and Allied Sciences*, 5(3), 208–212.
- Hong, J., Wang, C., Wagner, D. C., Gardea-Torresdey, J. L., He, F., & Rico, C. M. (2021). Foliar application of nanoparticles: Mechanisms of absorption, transfer, and multiple impacts. *Environmental Science. Nano*, 8, 1196–1210. <https://doi.org/10.1039/d0en01129k>
- Iqbal, M. (2016). *Vicia faba* bioassay for environmental toxicity monitoring: A review. *Chemosphere*, 144, 785–802. <https://doi.org/10.1016/j.chemosphere.2015.09.048>
- Iqbal, M., Raja, N. I., Hussain, M., Ejaz, M., & Yasmeen, F. (2019). Effect of silver nanoparticles on growth of wheat under heat stress. *Iranian Journal of Science and Technology, Transactions A: Science*, 43, 387–395. <https://doi.org/10.1007/s40995-017-0417-4.85>
- Javed, R., Khan, B., Sharafat, U., Bilal, M., Galagedara, L., Abbey, L., & Cheema, M. (2024). Dynamic interplay of metal and metal oxide nanoparticles with plants: Influencing factors, action mechanisms, and assessment of stimulatory and inhibitory effects. *Ecotoxicology and Environmental Safety*, 271, 115992. <https://doi.org/10.1016/j.ecoenv.2024.115992>

- Joško, I., Kusiak, M., Xing, B., & Oleszczuk, P. (2021). Combined effect of nano-CuO and nano-ZnO in plant-related system: From bioavailability in soil to transcriptional regulation of metal homeostasis in barley. *Journal of Hazardous Materials*, 416, 126230. <https://doi.org/10.1016/j.jhazmat.2021.126230>
- Kanakari, E., & Dendrinou-Samara, C. (2023). Fighting phytopathogens with engineered norganic-based nanoparticles. *Materials*, 16, 2388. <https://doi.org/10.3390/ma16062388>
- Khan, A., & Ahmad, F. (2022). Nanomaterials as unique carriers in agricultural practices for plant growth and development: A state of current knowledge. In J.-T. Chen (Ed.), *Plant and nanoparticles* (pp. 281–314). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-2503-0_11
- Khan, A. R., Wakeel, A., Muhammad, N., Liu, B., Wu, M., Liu, Y., Ali, I., Zaidi, S. H. R., Azhar, W., Song, G., Wua, J., & Gan, Y. (2019a). Involvement of ethylene signaling in zinc oxide nanoparticle-mediated biochemical changes in *Arabidopsis thaliana* leaves. *Environmental Science. Nano*, 1(6), 341–355. <https://doi.org/10.1039/C8EN00971F>
- Khan, M. R., Adam, V., Rizvi, T. F., Zhang, B., Ahamad, F., Jösko, I., Zhu, Y., Yang, M., & Mao, C. (2019b). Nanoparticle-plant interactions: Two-way traffic. *Small*, 15, 1901794. <https://doi.org/10.1002/smll.201901794>
- Khan, M. A., Khan, T., Riaz, M. S., Ullah, N., Ali, H., & Nadhman, A. (2019c). Plant cell nanomaterials interaction: Growth, physiology and secondary metabolism. *Comprehensive Analytical Chemistry*, 84, 23–54. <https://doi.org/10.1016/bs.coac.2019.04.005>
- Khan, M., Khan, M. S. A., Borah, K. K., Goswami, Y., Hakeem, K. R., & Chakrabarty, I. (2021). The potential exposure and hazards of metal-based nanoparticles on plants and environment, with special emphasis on ZnO NPs, TiO₂ NPs, and AgNPs. *Environmental Advances*, 6(80), 100128. <https://doi.org/10.1016/j.envadv.2021.100128>
- Khan, S., Zahoor, M., Khan, R. S., Muhammad Ikram, M., & Islam, N. U. (2023). The impact of silver nanoparticles on the growth of plants: The agriculture applications. *Heliyon*, 9, e16928. <https://doi.org/10.1016/j.heliyon.2023.e16928>
- Kouhi, S. M. M., Lahouti, M., Ganjeali, A., & Entezari, M. H. (2015). Long-term exposure of rapeseed (*Brassica napus* L.) to ZnO nanoparticles: Anatomical and ultrastructural responses. *Environmental Science and Pollution Research*, 22, 10733–10743.
- Kruszka, D., Selvakesavan, R. K., Kachlicki, P., & Franklin, G. (2022). Untargeted metabolomics analysis reveals the elicitation of important secondary metabolites upon treatment with various metal and metal oxide nanoparticles in *Hypericum perforatum* L. cell suspension cultures. *Industrial Crops and Products*, 178, 114561. <https://doi.org/10.1016/j.indcrop.2022.114561>
- Labeeb, M., Badr, A., Haroun, S. A., Mattar, M. Z., & El-kholy, A. S. (2022). Ultrastructural and molecular implications of ecofriendly made silver nanoparticles treatments in pea (*Pisum sativum* L.). *Journal of Genetic Engineering and Biotechnology*, 20, 5. <https://doi.org/10.1186/s43141-021-00285-1>
- Le Van, N., Ma, C., Shang, J., Rui, Y., Liu, S., & Xing, B. (2016). Effects of CuO nanoparticles on insecticidal activity and phytotoxicity in conventional and transgenic cotton. *Chemosphere*, 144, 661–670.
- Li, C., & Zhang, B. H. (2016). MicroRNAs in control of plant development. *Journal of Cellular Physiology*, 231, 303–313. <https://doi.org/10.1002/jcp.25125>
- Li, L. H., Yen, M. Y., Ho, C. C., Wu, P., Wang, C. C., Maurya, P. K., Chen, P. S., Chen, W., Hsieh, W. Y., & Chen, H. W. (2013). Noncytotoxic nanomaterials enhance antimicrobial activities of efmetazole against multidrug-resistant *Neisseria gonorrhoeae*. *PLoS One*, 8(5), 1–10. <https://doi.org/10.1371/journal.pone.0064794>
- Li, W. Q., Qing, T., Li, C. C., Li, F., Ge, F., Fei, J. J., & Peijnenburg, W. J. (2020). Integration of subcellular partitioning and chemical forms to understand silver nanoparticles toxicity to lettuce (*Lactuca sativa* L.) under different exposure pathways. *Chemosphere*, 258, 127349. <https://doi.org/10.1016/j.chemosphere.2020.127349>

- Lian, J., Liu, W., Meng, L., Wu, J., Chao, L., Zeb, A., & Sun, Y. (2021). Foliar-applied polystyrene nanoplastics (PSNPs) reduce the growth and nutritional quality of lettuce (*Lactuca sativa* L). *Environmental Pollution*, 280, 116978. <https://doi.org/10.1016/j.envpol.2021.116978>
- Limbach, L. K., Wick, P., Manser, P., Grass, R. N., Bruinink, A., & Stark, W. J. (2007). Exposure of engineered nanoparticles to human lung epithelial cells: Influence of chemical composition and catalytic activity on oxidative stress. *Environmental Science & Technology*, 41, 4158–4163.
- Liu, J., Dhungana, B., & Cobb, G. P. (2018). Environmental behavior, potential phytotoxicity, and accumulation of copper oxide nanoparticles and arsenic in rice plants. *Environmental Toxicology and Chemistry*, 37(1), 11–20. <https://doi.org/10.1002/etc.3945>
- Liu, L., Bai, X., Martikainen, M. V., Kårlund, A., Roponen, M., Xu, W., Hu, G., Tasciotti, E., & Lehto, V. P. (2021). Cell membrane coating integrity affects the internalization mechanism of biomimetic nanoparticles. *Nature Communications*, 12, 5726. <https://doi.org/10.1038/s41467-021-26052-x>
- Lv, J., Zhang, S., Luo, L., Zhang, J., Yang, K., & Christie, P. (2015). Accumulation, speciation and uptake pathway of ZnO nanoparticles in maize. *Environmental Science. Nano*, 2, 68–77. <https://doi.org/10.1039/C4EN00064A>
- Lv, J., Christie, P., & Zhang, S. (2019). Uptake, translocation, and transformation of metal-based nanoparticles in plants: Recent advances and methodological challenges. *Environmental Science. Nano*, 6, 41–59. <https://doi.org/10.1039/C8EN00645H>
- Magdolenova, Z., Collins, A., Kumar, A., Dhawan, A., Stone, V., & Dusinska, M. (2014). Mechanisms of genotoxicity. A review of *in vitro* and *in vivo* studies with engineered nanoparticles. *Nanotoxicology*, 8(3), 233–278.
- Mahmoud, L. M., Dutt, A. M., Shalan, M. E., El-Kady, M. S., El-Boray, Y. M., & Shabana, G. J. W. (2020). Silicon nanoparticles mitigate oxidative stress of *in vitro* derived banana (*Musa acuminata* ‘Grand Nain’) under simulated water deficit or salinity stress. *South African Journal of Botany*, 132, 155–163. <https://doi.org/10.1016/j.sajb.2020.04.027>
- Malandrakis, A. A., Kavroulakis, N., Avramidou, M., Papadopoulou, K. K., Tsaniklidis, G., & Chrysikopoulos, C. V. (2021). Metal nanoparticles: Phytotoxicity on tomato and effect on symbiosis with the *Fusarium solani* FsK strain. *Science of the Total Environment*, 787, 147606. <https://doi.org/10.1016/j.scitotenv.2021.147606>
- Manna, I., Mishra, S., & Bandyopadhyay, M. (2022). *In vivo* genotoxicity assessment of nickel oxide nanoparticles in the model plant *Allium cepa* L. *Nucleus*, 65, 203–214. <https://doi.org/10.1007/s13237-021-00377-w>
- Mittal, D., Kaur, G., Singh, P., Yadav, K., & Ali, S. A. (2020). Nanoparticle-based sustainable agriculture and food science: Recent advances and future outlook. *Frontiers in Nanotechnology*, 2, 579954. <https://doi.org/10.3389/fnano.2020.579954>
- Moradbeygi, H., Jamei, R., Reza Heidari, R., & Darvishzadeh, R. (2020). Investigating the enzymatic and non-enzymatic antioxidant defense by applying iron oxide nanoparticles in *Dracocephalum moldavica* L. plant under salinity stress. *Scientia Horticulturae*, 272, 109537. <https://doi.org/10.1016/j.scienta.2020.109537>
- Mozafari, A., Dedejani, S., & Ghaderi, N. (2018). Positive responses of strawberry (*Fragaria × ananassa* Duch.) explants to salicylic and iron nanoparticle application under salinity conditions. *Plant Cell Tissue and Organ Culture*, 134, 267–275. <https://doi.org/10.1007/s11240-018-1420-y>
- Mustafa, G., & Komatsu, S. (2016). Insights into the response of soybean mitochondrial proteins to various sizes of aluminum oxide nanoparticles under flooding stress. *Journal of Proteome Research*, 15(12), 4464–4475. <https://doi.org/10.1021/acs.jproteome.6b00572>
- Muzammil, S., Ashraf, A., Siddique, M. H., Aslam, B., Rasul, I., Abbas, R., Afzal, M., Faisal, M., & Hayat, S. (2023). A review on toxicity of nanomaterials in agriculture: Current scenario and future prospects. *Science Progress*, 106(4), 368504231221672. <https://doi.org/10.1177/00368504231221672>

- Nair, R., Mohamed, M. S., Gao, W., Maekawa, T., Yoshida, Y., Ajayan, P. M., & Kumar, D. S. (2012). Effect of carbon nanomaterials on the germination and growth of rice plants. *Journal of Nanoscience and Nanotechnology*, 12(3), 2212–2220. <https://doi.org/10.1166/jnn.2012.5775>
- Nawaz, M., Anjum, S. A., Ashraf, U., Azeem, F., & Wang, Z. (2021). Antioxidant defense system and reactive oxygen species (ROS) interplay in plants under drought condition. In J. M. Luetz & D. Ayala (Eds.), *Handbook of climate change management* (pp. 93–117). Springer. https://doi.org/10.1007/978-3-030-57281-5_121
- Nguyen, V. D., Nguyen, H. M., Le, N. T., Nguyen, K. H., Nguyen, H. T., Le, H. M., Nguyen, A. T., Dinh, N. T. T., Hoang, S. A., & Ha, C. V. (2022). Copper nanoparticle application enhances plant growth and grain yield in maize under drought stress conditions. *Journal of Plant Growth Regulation*, 41, 364–375. <https://doi.org/10.1007/s00344-021-10301-w>
- Nile, S. H., Thiruvengadam, M., Wang, Y., Samynathan, R., Shariati, M. A., Rebezov, M., Nile, A., Sun, M., Venkidasamy, B., Xiao, J., & Kai, G. (2022). Nano-priming as emerging seed priming technology for sustainable agriculture-recent developments and future perspectives. *Journal of Nanobiotechnology*, 20, 1–31. <https://doi.org/10.1186/s12951-022-01423-8>
- Nobahar, A., Carlier, J. D., Miguel, M. G., & Costa, M. C. (2021). A review of plant metabolites with metal inter-action capacity: A green approach for industrial applications. *Biometals*, 34(4), 761–793. <https://doi.org/10.1007/s10534-021-00315-y>
- Ozyigit, I. I., Filiz, E., Vatansever, R., Kurtoglu, K. Y., Koc, I., Oztürk, M. X., & Anjum, N. A. (2016). Identification and comparative analysis of H₂O₂-scavenging enzymes (ascorbate peroxidase and glutathione peroxidase) in selected plants employing bioinformatics approaches. *Frontiers in Plant Science*, 7, 301. <https://doi.org/10.3389/fpls.2016.00301>
- Palmqvist, N. M., Seisenbaeva, G. A., Svedlindh, P., & Kessler, V. G. (2017). Maghemite nanoparticles acts as nanozymes, improving growth and abiotic stress tolerance in *Brassica napus*. *Nanoscale Research Letters*, 12, 631. <https://doi.org/10.1186/s11671-017-2404-2>
- Pathakoti, K., Manubolu, M., & Hwang, H. (2018). Nanotechnology applications for environmental industry. In C. M. Hussain (Ed.), *Handbook of nanomaterials for industrial applications* (pp. 894–907). Elsevier. <https://doi.org/10.1016/B978-0-12-813351-4.00050-X>
- Pereira, E. S., Oliveira, H. C., Fraceto, L. F., & Santaella, C. (2021). Nanotechnology potential in seed priming for sustainable agriculture. *Nanomaterials*, 11(2), 10.3390/Nano11020267.
- Pérez-de-Luque, A. (2017). Interaction of nanomaterials with plants: What do we need for real applications in agriculture? *Frontiers in Environmental Science*, 5, 12. <https://doi.org/10.3389/fenvs.2017.00012>
- Pokharel, B. R., Sheri, V., Kumar, M., Zhang, Z., & Zhang, B. (2024). The update and transport of aluminum nanoparticles in plants and their biochemical and molecular phototoxicity on plant growth and development: A systematic review. *Environmental Pollution*, 340, 122875. <https://doi.org/10.1016/j.envpol.2023.122875>
- Pokhrel, L. R., & Dubey, B. (2013). Evaluation of developmental responses of two crop plants exposed to silver and zinc oxide nanoparticles. *Science of The Total Environment*, 452, 321–332.
- Polischuk, S. D., Fadkin, G. N., Churilov, D., Churilova, V. V., & Churilov, G. I. (2019). The stimulating effect of nanoparticle suspensions on seeds and seedlings of scotch pine (*Pinus sylvestris*). *IOP Conference Series: Earth and Environmental Science*, 226, 012020. <https://doi.org/10.1088/1755-1315/226/1/012020>
- Preetha, J. S., Sriram, D., Premasudha, P., Pudake, R. N., & Arun, M. (2023). Cerium oxide as a nanozyme for plant abiotic stress tolerance: An overview of the mechanisms. *Plant Nano Biology*, 6, 100049. <https://doi.org/10.1016/j.plana.2023.100049>
- Rahman, S. U., Wang, X., Shahzad, M., Bashir, O., Li, Y., & Cheng, H. (2022). A review of the influence of nanoparticles on the physiological and biochemical attributes of plants with a focus on the absorption and translocation of toxic trace elements. *Environmental Pollution*, 310, 119916. <https://doi.org/10.1016/j.envpol.2022.119916>

- Rajput, V. D., Minkina, T., Suskova, S., Mandzhieva, S., Tsitsuashvili, V., Chaplgin, V., & Fedorenko, A. (2018a). Effects of copper nanoparticles (CuO NPs) on crop plants: A mini review. *BioNanoScience*, 8, 36–42. <https://doi.org/10.1007/s12668-017-0466-3>
- Rajput, V., Minkina, T., Fedorenko, A., Sushkova, S., Mandzhieva, S., Lysenko, V., Duplii, N., Fedorenko, G., Dvadenko, K., & Ghazaryan, K. (2018b). Toxicity of copper oxide nanoparticles on spring barley (*Hordeum sativum distichum*). *Science of The Total Environment*, 645, 1103–1113. <https://doi.org/10.1016/j.scitotenv.2018.07.211>
- Rajput, V., Minkina, T., Sushkova, S., Behal, A., Maksimov, A., Blicharska, E., Ghazaryan, K., Movsesyan, H., & Barsova, N. (2020a). ZnO and CuO nanoparticles: A threat to soil organisms, plants, and human health. *Environmental Geochemistry and Health*, 42, 147–158. <https://doi.org/10.1007/s10653-019-00317-3>
- Rajput, V. D., Minkina, T., Sushkova, S., Mandzhieva, S., Fedorenko, A., Lysenko, V., Bederska-Blaszczyk, M., Olchowik, J., Tsitsuashvili, V., & Chaplygin, V. (2020b). Structural and ultrastructural changes in nanoparticle exposed plants. In R. N. Pudake et al. (Eds.), *Nanoscience for sustainable agriculture*. Springer. https://doi.org/10.1007/978-3-319-97852-9_13
- Raliya, R., Franke, C., Chavalmane, S., Nair, R., Reed, N., & Biswas, P. (2016). Quantitative understanding of nanoparticle uptake in watermelon plants. *Frontiers in Plant Science*, 7, 1288. <https://doi.org/10.3389/fpls.2016.01288>
- Rashad, Y. M., El-Sharkawy, H. H. A., Belal, B. E. A. A., Abdel Razik, E. S., & Galilah, D. A. (2021). Silica nanoparticles as a probable anti-oomycete compound against downy mildew, and yield and quality enhancer in grapevines: Field evaluation, molecular, physiological, ultrastructural, and toxicity investigations. *Frontiers in Plant Science*, 12, 763365. <https://doi.org/10.3389/fpls.2021.763365>
- Rasheed, A., Li, H., Tahir, M. M., Mahmood, A., Nawaz, M., Shah, A. N., Aslam, M. T., Negm, S., Moustafa, M., Hassan, M. U., & Wu, Z. (2022). The role of nanoparticles in plant biochemical, physiological, and molecular responses under drought stress: A review. *Frontiers in Plant Science*, 13, 976179. <https://doi.org/10.3389/Fpls.2022.976179>
- Rezayian, M., Niknam, V., & Arabloo, M. (2023). Iron nanoparticle regulate succinate dehydrogenase activity in canola plants under drought stress. *Scientific Reports*, 13, 9628. <https://doi.org/10.1038/s41598-023-36105-4>
- Riaz, A., Deng, F., Chen, G., Jiang, W., Zheng, Q., Riaz, B., Mak, M., Zeng, F., & Chen, Z. H. (2022). Molecular regulation and evolution of redox homeostasis in photosynthetic machinery. *Antioxidants*, 11(11), 2085. <https://doi.org/10.3390/antiox11112085>
- Rossi, L., Fedenia, L. N., Sharifan, H., Ma, X., & Lombardini, L. (2019). Effects of foliar application of zinc sulfate and zinc nanoparticles in coffee (*Coffea arabica* L.) plants. *Plant Physiology and Biochemistry*, 135, 160–166. <https://doi.org/10.1016/j.plaphy.2018.12.005>
- Sable, S. V., Ranade, S., & Joshi, S. (2018). Role of AgNPs in the enhancement of seed germination and its effect on plumule and radicle length of *Pennisetum glaucum*. *IET Nanobiotechnology*, 12, 922–926. <https://doi.org/10.1049/iet-nbt.2017.0304>
- Selvakesavan, R. K., Kruska, D., Shaky, P., Mondal, D., & Franklin, G. (2023). Impact of nanomaterials on plant secondary metabolism. In J. M. Al-Khayri et al. (Eds.), *Nanomaterial interactions with plant cellular mechanisms and macromolecules and agricultural implications*. Springer. https://doi.org/10.1007/978-3-031-20878-2_6
- Shang, Y., Hasan, K. M., Ahammed, G. J., Li, M., Yin, H., & Zhou, J. (2019). Applications of nanotechnology in plant growth and crop protection: A review. *Molecules*, 24, 2558. <https://doi.org/10.3390/molecules24142558>
- Shaw, A. K., & Hossain, Z. (2013). Impact of nano-CuO stress on rice (*Oryza sativa* L.) seedlings. *Chemosphere*, 93, 906–915.
- Shyam, R., & Aery, N. C. (2012). Effect of cerium on growth, dry matter production, biochemical constituents and enzymatic activities of cowpea plants [*Vigna unguiculata* (L.) Walp.]. *Journal of Soil Science and Plant Nutrition*, 12(1), 1–14. <https://doi.org/10.4067/S0718-95162012000100001>

- Simkin, A. J., Kapoor, L., Doss, C. G. P., Hofmann, T. A., Lawson, T., & Ramamoorthy, S. (2022). The role of photosynthesis related pigments in light harvesting, photoprotection and enhancement of photosynthetic yield in planta. *Photosynthesis Research*, 152, 23–42. <https://doi.org/10.1007/s11120-021-00892-6>
- Singh, A., Singh, N. B., Hussain, I., Singh, H., & Singh, S. C. (2015). Plant-nanoparticle interaction: An approach to improve agricultural practices and plant productivity. *International Journal of Pharmaceutical Science Invention*, 4, 25–40.
- Singh, A., Singh, N. B., Hussain, I., & Singh, H. (2017). Effect of biologically synthesized copper oxide nanoparticles on metabolism and antioxidant activity to the crop plants *Solanum lycopersicum* and *Brassica oleracea* var. *botrytis*. *Journal of Biotechnology*, 262, 11–27. <https://doi.org/10.1016/j.jbiotec.2017.09.016>
- Singh, A., Singh, N. B., Afzal, S., Singh, T., & Hussain, I. (2018). Zinc oxide nanoparticles: A review of their biological synthesis, antimicrobial activity, uptake, translocation and biotransformation in plants. *Journal of Materials Science*, 53(1), 185–201. <https://doi.org/10.1007/s10853-017-1544-1>
- Singh, R. P., Handa, R., & Manchanda, G. (2021). Nanoparticles in sustainable agriculture: An emerging opportunity. *Journal of Controlled Release*, 329, 1234–1248. <https://doi.org/10.1016/j.jconrel.2020.10.051>
- Singh, A., Sengar, R. S., Rajput, V. D., Agrawal, S., Ghazaryan, K., Minkina, T., Al Tawaha, A., Al Zoubi, O. M., & Habeeb, T. (2023). Impact of zinc oxide nanoparticles on seed germination characteristics in rice (*Oryza Sativa* L.) under salinity stress. *Journal of Ecological Engineering*, 24(10), 142–156. <https://doi.org/10.12911/22998993/169142>
- Singla, R., Kumari, A., & Yadav, S. K. (2019). Impact of nanomaterials on plant physiology and functions. In A. Husen & M. Iqbal (Eds.), *Nanomaterials and plant potential*. Springer. https://doi.org/10.1007/978-3-030-05569-1_14
- Song, G., Gao, Y., Wu, H., Hou, W., Zhang, C., & Ma, H. (2012). Physiological effect of anatase TiO₂ nanoparticles on *Lemna minor*. *Environmental Toxicology and Chemistry*, 31, 2147–2152. <https://doi.org/10.1002/etc.1933>
- Sui, H. J., Zhang, J. Z., & Wang, Z. Y. (2014). Toxicity of copper oxide engineered nanoparticles to maize (*Zea mays* L.) at different aging times. *Advanced Materials Research*, 881–883, 972–975. <https://doi.org/10.4028/www.scientific.net/AMR.881-883.972>
- Sukumaran, S., & Grant, A. (2013). Effects of genotoxicity and its consequences at the population level in sexual and asexual *Artemia* assessed by analysis of inter-simple sequence repeats (ISSR). *Mutation Research*, 757, 8–14.
- Sun, Y., Wang, W., Zheng, F., Zhang, S., Wang, F., & Liu, S. (2020). Phytotoxicity of iron-based materials in mung bean: Seed germination tests. *Chemosphere*, 251, 126432. <https://doi.org/10.1016/j.chemosphere.2020.126432>
- Sun, H., Qu, G., Li, S., Song, K., Zhao, D., Li, X., Yang, P., He, X., & Hu, T. (2024). Corrigendum to “iron nanoparticles induced the growth and physio-chemical changes in *Kobresia capillifolia* seedlings” [Plant Physiol. Biochem. 194 (2023) 15–28]. *Plant Physiology and Biochemistry*, 210, 108431. <https://doi.org/10.1016/j.plaphy.2024.108431>
- Szöllősi, R., Molnár, Á., Kondak, S., & Kolbert, Z. (2020). Dual effect of nanomaterials on germination and seedling growth: Stimulation vs. phytotoxicity. *Plants*, 9(12), 1745. <https://doi.org/10.3390/plants9121745>
- Tabatabaee, S., Iranbakhsh, A., Shamili, M., & Ardebili, Z. O. (2021). Copper nanoparticles mediated physiological changes and transcriptional variations in microRNA159 (*miR159*) and mevalonate kinase (*MVK*) in pepper; potential benefits and phytotoxicity assessment. *Journal of Environmental Chemical Engineering*, 9, 106151. <https://doi.org/10.1016/j.jece.2021.106151>
- Takshak, S., & Agrawal, S. (2019). Defense potential of secondary metabolites in medicinal plants under UV-B stress. *Journal of Photochemistry and Photobiology B: Biology*, 193, 51–88. <https://doi.org/10.1016/J.jphotobiol.2019.02.002>

- Tang, Y. J., Wu, S. G., Huang, L., Head, J., Chen, D., & Kong, I. C. (2013). Phytotoxicity of metal oxide nanoparticles is related to both dissolved metals ions and adsorption of particles on seed surfaces. *Journal of Petroleum & Environmental Biotechnology*, 3, 126–130.
- Thiruvengadam, M., Chi, H. Y., & Kim, S. H. (2024). Impact of nanopollution on plant growth, photosynthesis, toxicity, and metabolism in the agricultural sector: An updated review. *Plant Physiology and Biochemistry*, 207, 108370. <https://doi.org/10.1016/j.plaphy.2024.108370>
- Tombuloglu, H., Slimani, Y., AlShammari, T. M., Bargouti, M., Ozdemir, M., Tombuloglu, G., Akhtar, S., Sabit, H., Hakeem, K. R., Almessiere, M., Ercan, I., & Baykal, A. (2020). Uptake, translocation, and physiological effects of hematite ($\alpha\text{-Fe}_2\text{O}_3$) nanoparticles in barley (*Hordeum vulgare* L.). *Environmental Pollution*, 266(1), 1115391. <https://doi.org/10.1016/j.envpol.2020.1115391>
- Torabian, S., Farhangi-Abriz, S., & Zahedi, M. (2018). Efficacy of FeSO_4 nano formulations on osmolytes and antioxidative enzymes of sunflower under salt stress. *Indian Journal of Plant Physiology*, 23, 305–315. <https://doi.org/10.1007/s40502-018-0366-8>
- Wang, H., Wu, F., Meng, W., White, J. C., Holden, P. A., & Xing, B. (2013). Engineered nanoparticles may induce genotoxicity. *Environmental Science & Technology*, 47, 13212–13214. <https://doi.org/10.1021/es404527d>
- Wang, X., Yang, X., Chen, S., Li, Q., Wang, W., Hou, C., Gao, X., Wang, L., & Wang, S. (2016). Zinc oxide nanoparticles affect biomass accumulation and photosynthesis in *Arabidopsis*. *Frontiers in Plant Science*, 6, 1243. <https://doi.org/10.3389/fpls.2015.01243>
- Wang, Y., Lin, Y., Xu, Y., Yin, Y., Guo, H., & Du, W. (2019). Divergence in response of lettuce (var. *ramosa* Hort.) to copper oxide nanoparticles/microparticles as potential agricultural fertilizer. *Environmental Pollutants and Bioavailability*, 31, 80–84. <https://doi.org/10.1080/26395940.2019.1578187>
- Wang, L., Sun, J., Lin, L., Fu, Y., Alenius, H., Lindsey, K., & Chen, C. (2020). Silver nanoparticles regulate *Arabidopsis* root growth by concentration-dependent modification of reactive oxygen species accumulation and cell division. *Ecotoxicology and Environmental Safety*, 190, 110072. <https://doi.org/10.1016/j.ecoenv.2019.110072>
- Xu, L., Wang, Y., Huang, J., Chen, C., Wang, Z., & Xie, H. (2020). Silver nanoparticles: Synthesis, medical applications and biosafety. *Theranostics*, 20(10), 8996–9031.
- Yin, S., Liu, J., Kang, Y., Lin, Y., Li, D., & Shao, L. (2019). Interactions of nanomaterials with ion channels and related mechanisms. *British Journal of Pharmacology*, 176(19), 3754–3774. <https://doi.org/10.1111/bph.14792>
- Youssef, M. S., & Elamawi, R. M. (2020). Evaluation of phytotoxicity, cytotoxicity, and genotoxicity of ZnO nanoparticles in *Vicia faba*. *Environmental Science and Pollution Research*, 16(27), 18972–18984. <https://doi.org/10.1007/s11356-018-3250-1>
- Zafar, H., Javed, R., & Zia, M. (2023). Nanotoxicity assessment in plants: An updated overview. *Environmental Science and Pollution Research*, 30, 93323–93344. <https://doi.org/10.1007/s11356-023-29150-z>
- Zhang, P., Ma, Y., & Zhang, Z. (2015). Interactions between engineered nanomaterials and plants: Phytotoxicity, uptake, translocation, and biotransformation. In *Nanotechnology and plant sciences: Nanoparticles and their impact on plants* (p. 77). Springer. https://doi.org/10.1007/978-3-319-14502-0_5
- Zhang, P., Ma, Y., Liu, S., Wang, G., Zhang, J., He, X., Zhang, J., Rui, Y., & Zhang, Z. (2017). Phytotoxicity, uptake and transformation of nano- CeO_2 in sand cultured romaine lettuce. *Environmental Pollution*, 220, 1400–1408. <https://doi.org/10.1016/j.envpol.2016.10.094>
- Zheng, L., Hong, F., Lu, S. P., & Liu, C. (2005). Effect of nano- TiO_2 on strength of naturally and growth aged seeds of spinach. *Biological Trace Element Research*, 104, 83–91. <https://doi.org/10.1385/bter:104:1:083>

Chapter 11

Antifungal Activity of Metal-Based Nanomaterial and Their Morph-Physiological Responses on Plants



Sozan E. El-Abeid and Abeer A. Ali

Abstract The annual crop losses caused by living organisms (biotic stress) and abiotic factors range from 50–60%. In agriculture fields, multiple stressors often occur concurrently, impacting plant development and overall yield. Among these stressors, plant pathogenic fungi pose significant risks due to their genetic and structural diversity. However, their rapid adaptability to environmental changes makes it challenging to devise a universal strategy for managing fungal disease. An integrated approach is essential, including antifungal agents, fungicides, and targeted strategies specific to individual fungus species. This chapter focuses on the ability of nanotechnology to enhance plant disease control. Top-down or bottom-up (wet chemistry and biosynthesis) nanotechnology transforms bulk organic or inorganic materials into nanoparticles. Depending on their unique characteristics, such as a small dimension that facilitates their translocation, a large surface area that increases the interaction region, and surface reactivity, nanoparticles have unique physicochemical and biological features. Nanomaterials of metal or metal oxide may inhibit fungal growth. Metal ions like Ag⁺ (silver), Au³⁺ (gold), Cu²⁺ (copper), and Zn²⁺ (zinc) oxid NPs, and release metal ions that generate reactive oxygen species (ROS). These species can disrupt microorganisms by interfering with critical biochemical pathways or essential cellular structures, providing an innovative approach to combating fungal infections.

Keywords Metal-based nanomaterial · Antifungal properties · Impact of metal NPs · Morpho-physiological · Nanomaterial as fungicides · Mode of action

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11.1 Introduction

Fungal infections have significantly impacted the quantity and quality of grain yields, vegetable crops, and fruits. The shift from micro-sized mineral materials to nano-sized counterparts has enabled the development of novel materials with unique properties, making them suitable for agricultural applications, including crop protection (Ortiz & Sansinenea, 2022; Harman et al., 2021). Metals and their compounds have gained substantial attention due to their various applications across industry, agriculture, biomedicine, and nanotechnology. Coordination compounds derived from metals serve effectively as fungicides and antimicrobial agents (Cruz-Luna et al., 2021). Nanoparticles, a novel class of metal-based compounds, exhibit unique physicochemical, redox, optoelectronic, and morphological properties (Li et al., 2023). Nanotechnology, medicine, agriculture, pharmaceuticals, and related fields have further exploited these characteristics (Shende et al., 2021). Among transition metals, metal-based nanoparticles deserve attention for their physical, chemical, and antimicrobial attributes. Quantum size effects, surface properties, and changes in shape (like triangles, prisms, pentagons, and hexagons) can make antioxidant, antibacterial, antifungal, antiviral, and anti-inflammatory properties stronger. This means that metal-based nanoparticles can be used to protect plants from pathogens like *Fusarium* sp., *Alternaria* sp., and *Penicillium* sp. Researchers have applied these nanoparticles to a variety of crops, such as sugarcane, soybean, tomato, and corn (Kumar et al., 2021; Jiang et al., 2022).

Notably, silver, gold, zinc, and copper nanoparticles have shown promise in enhancing plant growth without toxicity. These nanoparticles can boost crop productivity by approximately 20% (Hafeez et al., 2015) and reduce disease incidence by approximately 50%. Additionally, inorganic nanomaterials effectively mitigate abiotic stress, crucial for maintaining plant health under adverse conditions. Biosynthesizing these nanoparticles using plant extracts offers an environmentally friendly approach, minimizing toxicity compared to traditional methods (Francis et al., 2024). While fungicides have long been essential for managing fungal diseases in various plant tissues (leaves, roots, and fruits), recent advancements focus on nitrogen-based heterocyclic compounds like diazines. These compounds enhance efficacy by targeting unique biological mechanisms, such as cell wall synthesis and protein inhibition (Saeedian Moghadam et al., 2024). However, the use of fungicides with similar modes of action has led to the development of resistance in numerous fungal species, complicating the management of diseases (Yin et al., 2023). Despite these challenges, fungicides remain a cornerstone of crop protection, with ongoing research exploring innovative resistance management strategies and new compounds to combat resistant strains (Toffolatti et al., 2024). Additionally, many investigations have provided evidence that copper oxide nanoparticles (CuO) synergistically interact with conventional fungicides like tebuconazole, thiophanate-methyl, fluazinam, and iprodione (Malandrakis et al., 2020; Parada et al., 2024). Additionally, biogenic nanofungicides are being developed to improve agrochemical delivery, enhancing crop protection and pathogen control through tailored nanomaterial properties.



Types of metal-based nanomaterials
Antifungal activity of metal-based nanomaterials
Metal-based Nanomaterials and their Morphological modifications on plants
Metal-based Nanomaterials and their physiological Responses on plants
The uptake and accumulation
Compare the efficacy of nanomaterial with fungicides and investigate their mode of action.

Fig. 11.1 Outline of the presented chapter

(Chauhan et al., 2024). Copper-based nanomaterials have demonstrated superior antifungal activity compared to conventional copper hydroxide formulations, suggesting their potential to reduce the environmental risks associated with traditional pesticides (Yuan et al., 2023).

Various nanomaterials have been identified for targeting fungi that infect leaves, roots, and fruits. Each nanomaterial demonstrates a unique antagonistic action. Through the generation of ROS, Zinc oxide (ZnO) nanoparticles exhibit efficacious antifungal activity against *Ascochyta fabae*, a pathogen affecting beans. This is achieved by disrupting fungal cell structures and inhibiting fungal growth (Sharma et al., 2023). Additionally, metal nanoparticles, including those synthesized through green methods, also leverage ROS to exert antifungal effects, targeting fungal cell walls and membranes (Lyagin et al., 2023). Furthermore, the integration of nanosensors for the early detection of fungal pathogens is a promising advancement in disease management (Nizamani et al., 2024). Finally, we will present an exploration of whether nanomaterials can serve as equivalent alternatives to fungicides. This chapter, as categorized in Fig. 11.1 mainly explores first, categorizes the uses of nanomaterials. Secondly, we have provided a concise overview of the antifungal properties exhibited by certain metal nanoparticles. Additionally, emphasizes their morpho-physiological responses. Third, compare the efficacy of nanomaterial with fungicides and investigate their mode of action.

11.2 Types of Metal-Based Nanomaterials

The antimicrobial (antifungal and antibacterial) properties of metal-based nanomaterials show great potential for agricultural applications. The potent antimicrobial properties of metal-nanoparticles, including silver, zinc oxide, copper, and gold, have gained significant attention. These particles are available in their purified form or loaded onto a variety of materials, such as magnetic fluids. Researchers

employ various biophysical and chemical methods to synthesize these metal-based nanomaterials (Singh et al., 2021). One interesting area of research involves studying the interaction between nanoparticles and different plant species, as well as their interactions with pathogens, based on the pathogen type, plant species, and the unique characteristics of the nanoparticles.

Copper (Cu) Nanoparticles

Many research papers investigated copper nanoparticles and found that this material is effective against *Botrytis cinerea* (gray mold), *Fusarium* spp., *Alternaria* spp., and *Colletotrichum* spp. The antifungal mechanism of copper nanomaterial involves the generation of ROS, damaging fungal cell membranes, and interference with fungal metabolism. To effectively manage fungal plant diseases like *Botrytis cinerea* and *Fusarium oxysporum*, it is important to explore the utilization of copper nanoparticles (NPs) (Parada et al., 2024). Additionally, investigated the ability of copper nanoparticles to disrupt fungal cell membranes and inhibit spore germination, making them a promising antifungal agent in agriculture. El-Abeid et al. (2024) examined the synergistic effects of copper nanoparticles and a plant-derived antifungal substance synthesized by green methods. The research focused on *Fusarium solani*, a common pathogen causing tomato root rot disease. Remarkably, this combination of copper and *ziziphus-spina-Christi*-derived compound exhibited significantly enhanced antifungal activity compared to either component alone.

Zinc Oxide (ZnO) Nanoparticles

ZnO nanoparticles exhibit both advantageous and negative impacts when used on plant treatments. While at minimal concentrations, ZnONPs can promote plant growth. By facilitating nutrient absorption and utilization. However, at higher doses, ZnONPs can be toxic to plants, leading to oxidative stress, reduced photosynthesis, and stunted growth, that effective against *Aspergillus* spp., *Penicillium* spp., *Fusarium* sp., and *Botrytis cinerea*. ZnO nanoparticles possess the ability to generate reactive oxygen species (ROS), cause disruptions in cell membranes, and interfere with the activities of fungal enzymes, which are all factors that contribute to their antifungal action (Mouhamad et al., 2022; Parada et al., 2024). In addition, ZnO NPs physically inhibit fungal hyphae and suppress the growth of pathogenic fungi, thus improving plant growth. Additionally, depending on their size, the production of nanoparticles and the enhancement of their antifungal activity against plant diseases can be achieved by the utilization of plant extracts. Ibrahim et al. (2024) investigate the ability of ZnONPs to inhibit infection of *Fusarium graminearum*. The nanoparticles showed effectiveness in reducing fungal growth and mycotoxin production.

Silver-Based Nanoparticles (AgNPs)

AgNPs have a great ability to control a wide range of fungal species, including *Candida* spp., *Penicillium* spp., *Fusarium* spp., *Aspergillus* spp., and *Alternaria* spp. The antifungal efficacy of silver nanoparticles is due to their ability to harm cell membranes, induce oxidative stress, and hinder fungal enzymes. Silver nanoparticles

have been found to have negative impacts on plant health, particularly at elevated quantities. Exposure to silver NPs can cause oxidative stress in plants, resulting in decreased biomass, reduced root and shoot development, and reduced photosynthetic efficiency. At lower concentrations, silver nanoparticles have been shown to activate antioxidant enzymes, consequently boosting defense mechanisms to reduce oxidative damage (Mouhamad et al., 2022).

Gold (Au)-Based Nanoparticles

Compared to other metal nanoparticles, AuNPs are commonly believed to have a beneficial effect on plant health when used. Scientific studies have shown that certain plant-based antioxidant enzymes, such as peroxidases, superoxide dismutase, and catalase, may be activated by the addition of gold nanoparticles. Plants can benefit from reduced oxidative stress and enhanced development and growth when antioxidant enzyme activity is increased (Manaf et al., 2021).

Iron (Fe) Nanoparticles

Iron oxide nanoparticles have complex antifungal and antibacterial mechanisms. It showed significant antifungal activity and inhibition in spore germination against *Cladosporium herbarum*, *Trichothecium roseum*, *Alternaria alternata*, *Aspergillus flavus*, and *Aspergillus niger* (Parveen et al., 2018). Furthermore, they interact with fungal proteins, leading to deactivation and disruption of DNA, inhibiting replication. Due to their unique size that allows them to penetrate the cell membranes, causing rupture and lysis. FeO nanoparticles disrupt fungal spores inhibiting cell division and inducing cell death. On the other hand, they can induce oxidative stress by generating ROS, causing oxidative damage that is effective against fungi and bacteria. Researchers enhance their properties through surface modifications like chitosan coating (Bharathi et al., 2019) and hybrid nanoparticle combinations such as Ag-FeO or Cu-FeO (Padilla-Cruz et al., 2021; Ali et al., 2023). These optimizations improve stability, biocompatibility, and antimicrobial activity. Moreover, iron nanoparticles' effects on plants might be harmless or harmful, based on the concentration of the nanoparticles and the kind of plant being studied. When present in low concentrations, iron nanoparticles have the potential to act as a micronutrient by boosting plant vigor. Nevertheless, oxidative stress may be induced by iron nanoparticles at raised concentrations and inhibit plant growth, leading to chlorosis (yellowing of leaves) and reduced biomass (Azadi et al., 2024; Sandhu et al., 2024).

Titanium Dioxide (TiO₂) Nanoparticles

Exposure of wheat plants to Titanium Dioxide nanoparticles produced with *Moringa oleifera* Lam. plant extract resulted in several morphological modifications including increased surface area of plant parts, plant biomass, and improved crop production. In parallel, physiological changes including the content of water, stability of cell membrane, and chlorophyll levels were observed, enhancing stress resistance and physiological functions. Biochemical changes are also indicated to enhance defense strategy (Mustafa et al., 2021).

11.3 Antifungal Activity of Metal-Based Nanomaterials

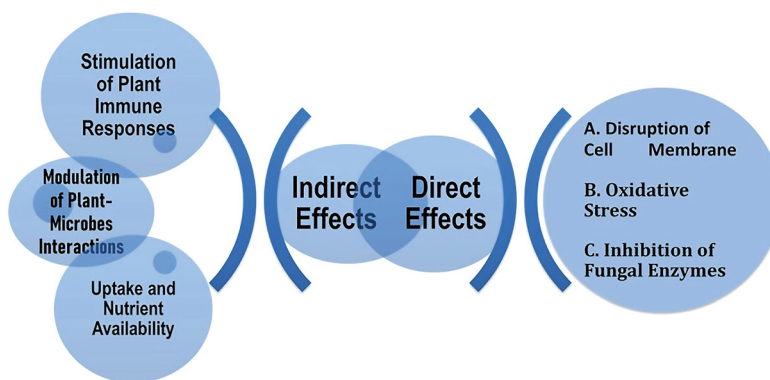
Nano-biotechnology is a promising field with great potential to revolutionize agriculture and plant science. The field of Nanofungicide in plant protection is still in its growing stage. The antifungal activity of metal-based nanomaterial is attributed to both direct and indirect effects on fungi, as illustrated in (Fig. 11.2).

11.3.1 Direct Effects

Direct antifungal activity refers to the ability of metal-based nanomaterials to directly disrupt and interact with the fungal cells, leading to their inhibition or death.

(a) Disruption of Cell Membrane:

Metal-based nanomaterial exhibits significant antifungal activity primarily through the deteriorating fungal cell membranes and producing reactive oxygen species (ROS). For instance, cerium oxide nanoparticles (CeO_2) have been shown to inhibit fungal growth by inducing ROS production, which affects cellular processes and leads to growth inhibition in fungi like *Aspergillus* sp. (Verma et al., 2022). Similarly, $\text{Fe}_3\text{O}_4@\text{SiO}_2/\text{Schiff-base}/\text{Cu(II)}$ magnetic nanoparticles demonstrated strong antifungal effects against various *Candida* species, attributed to their ability to disrupt the cell wall and membrane while also generating ROS (Azadi et al., 2024). Recent studies on metallic nanomaterials highlight that metal nanoparticles can lead to the accumulation of ROS, which non-specifically harm various bio-molecules, including those in cell membranes. Metal-based nanomaterials,



Antifungal activity of metal-based nanomaterial on fungal disease management

Fig. 11.2 The antifungal activity of metal-based nanomaterials can be connected with both direct and indirect effects on fungi

including silver, copper, and zinc oxide nanoparticles can bind to fungal cell membranes, which produces structural and functional alterations. This disruption may result in the leakage of cellular contents, reduced nutrition and ion transport, and subsequently, cell death. The study focuses on cerium oxide nanoparticles' antifungal effects on *Aspergillus oryzae*, inhibiting spore germination and growth through ROS production and influencing cellular responses, rather than cell membrane disruption (Nishino et al., 2024). The $\text{Fe}_3\text{O}_4@\text{SiO}_2/\text{Schiff-base}/\text{Cu}$ (II) magnetic nanoparticles disrupt fungal cell walls and membranes, exhibiting potent antifungal activity against *Candida* species, as indicated in the study (Azadi et al., 2024). Metallic nanoparticles disrupt fungal cell membranes, showcasing potent antifungal activity. Gold, copper, silver, iron oxide, and zinc oxide nanoparticles exhibit efficacy against various pathogenic fungi (Madkhali, 2023). Metal-based nanomaterials exhibit antifungal activity by disrupting cell membranes. Bioengineered nanomaterial coatings show promise in enhancing antimicrobial properties for various applications, including medical textiles. The study shows that copper oxide nanoparticles disrupt the cell membranes of *Botrytis cinerea* and *Fusarium oxysporum*, indicating potential antifungal activity through protein and nucleic acid release mechanisms (Parada et al., 2024). Using *Aspergillus fumigatus* filtrate to produce bimetallic AgNPs has the potential to damage bacterial membranes, release cellular contents, and demonstrate antifungal activity through cell membrane disruption (Saqib et al., 2022). Metal nanoparticles disrupt fungal cell membranes by damaging vital enzymes in the respiratory chain, leading to inhibitory effects on pathogenic fungi. Their antifungal activity is enhanced by this mechanism (Nisar et al., 2019).

(b) Oxidative Stress

Reactive oxygen species may be generated by metal-based nanomaterials within fungal cells which can lead to oxidative damage. Additionally, it can disrupt cellular components such as proteins, nucleic acid (DNA), and lipids, ultimately leading to fungal cell death. Metal nanoparticles disrupt fungal cell membranes by eliciting ROS generation (Lyagin et al., 2023; El-Abeid et al., 2024). Metal-based nanocomposites disrupt fungal cell membranes, including altering membrane organization and oxidative stress. Chitosan-based-silica, copper, and zinc nanocomposites exhibit potent antifungal efficacy against soil-borne pathogen (*F. solani*) and leaf pathogen *Alternaria solani* (Krumova et al., 2024).

(c) Inhibition of Fungal Enzymes

Some metal-based nanomaterials can interact with and inhibit the activity of essential fungal enzymes, disrupting various metabolic processes and impairing the fungal cells' ability to function properly. Metal nanomaterials trigger ROS generation, disrupting fungal cell membranes. Enzymes like glucanases and proteases also target fungal cell structures, enhancing antifungal activity synergistically. Metal nanoparticles disrupt Enzymes like glucanases and proteases and further enhance antifungal action by targeting various fungal components (Lyagin et al., 2023).

11.3.2 Indirect Effects

Indirect antifungal activity refers to the ability of metal-based nanomaterials to induce or enhance the defense mechanisms against plant pathogenic fungi.

(a) Stimulation of Plant Immune Responses

Metal-based nanomaterials can activate defense signaling pathways in plants, leading to the enhancement of antimicrobial compounds, such as phytoalexins, and the activation of defense-related enzymes. Metal-based nanomaterials exhibit significant antifungal activity by stimulating plant immune responses, as evidenced by various studies. For instance, cerium oxide nanoparticles (CeO_2) demonstrated fungistatic effects against *Aspergillus oryzae*, inhibiting spore germination, which is linked to enhanced plant defense mechanisms (Nishino et al., 2024). Bimetallic $\text{ZnO-B}_2\text{O}_3$ nanoparticles have shown promising antifungal properties against *Pythium irregulare*, reducing disease severity in pea plants and enhancing enzymatic activities. The study investigates the effects of these nanoparticles on pea plants' immunity against the damping-off disease caused by the pathogen. The main points include improved metabolic resistance indicators. The use of bimetallic $\text{ZnO-B}_2\text{O}_3$ NPs increased the activities of important enzymes in both diseased and uninfected pea plants, including polyphenol oxidase (PPO) and peroxidase (POD). Higher enzyme activity is often associated with improved plant defense mechanisms against pathogens. Reduction of malondialdehyde (MDA) content, a marker of oxidative stress in plants, indicates reduced cellular damage and stress. The study also reported decreased hydrogen peroxide (H_2O_2) levels suggesting reduced oxidative stress and improved recovery from infection, further indicating enhanced immunity (Elkhodary et al., 2023). When nanoparticles come into contact with phytopathogens, they can trigger the release of metal ions that disrupt microbial cell integrity and activate plant defense pathways (Pattanayak et al., 2023). Furthermore, copper-based nanofungicides are emerging as effective agrochemicals, promoting plant growth while minimizing environmental impact (Rajwade et al., 2024).

(b) Modulation of Plant-Microbes Interactions

Metal-based nanomaterials can alter the plant's microbiome, suppressing pathogenic fungi while promoting beneficial fungi, thus enhancing plant resistance to fungal diseases. Nanoparticles (NPs) significantly modulate plant-microbe interactions, affecting both microbial communities and plant health. They can enhance microbial growth and nutrient cycling by improving soil nutrient availability, but excessive concentrations may lead to toxicity, reducing microbial diversity and functionality. NPs also interact with plant cells, causing oxidative stress that can either inhibit physiological processes or stimulate growth, subject to the nanoparticles' Kind and amount.

They can also disrupt microbial cell structures, leading to cell damage and reduced microbial biomass, which is pivotal for maintaining soil health and plant productivity (Hussain et al., 2023). While NPs offer potential benefits in agriculture,

such as improved disease resistance and nutrient delivery, their impact on beneficial microbial symbionts requires careful application to avoid negative effects on soil ecosystems. Responsible use and further research are essential to balance the advantages of NPs with their environmental implications. Discovering how NPs interact with soil microbiomes is essential for developing environmentally friendly agricultural practices that maximize crop yields while preserving ecological integrity (Mishra et al., 2021).

Nanoparticles can both positively and negatively impact plant-microbe interactions by influencing soil properties, microbial communities, and environmental health. They increase plant defenses through interactions with PGPR, antioxidant enzymes, and protective solutes, therefore enhancing plant health, productivity, and stress tolerance (Kapoor et al., 2023). Ongoing research aims to explore how nanoparticles interact with both plants and microbes, leading to the development of innovative agricultural practices (Ameen et al., 2021). Biogenic gold nanoparticles enhance growth hormone “indole acetic acid” production by stimulating *Pseudomonas aeruginosa* bacteria by improving plant vigor (Panichikkal & Krishnankutty, 2022). Metal oxide nanoparticles can modulate plant-microbe interactions by influencing the rhizosphere environment, potentially affecting the PGPR activity and ultimately impacting plant development and production (Niu & Zhang, 2023; Patel et al., 2023). Biosynthesized silver nanoparticles modulate plant-microbe interactions by reducing fungal spores and lesions without affecting soil microflora diversity or enzyme activities, showing potential for plant disease management (Shende et al., 2021).

(c) Uptake and Nutrient Availability

Metal-based nanomaterials significantly enhance nutrient uptake and availability in plants through several mechanisms. In particular, their reactive behavior and large surface area are distinctive physicochemical features that facilitate the efficient delivery of micronutrients like zinc and iron, which are crucial for plant health (Francis et al., 2024). Moreover, the application of nanomaterial mitigates the limitations of traditional fertilizers by enhancing bioavailability and reducing nutrient losses (Santás-Miguel et al., 2023). Nanoparticles (NPs) contribute to increased ion exchange in the soil, which is necessary for the uptake of nutrients by plants.

11.4 Metal-Based Nanomaterials and Their Morphological Modifications on Plants

The term “morphological modification” refers to the various ways in which nanoparticles (NPs) can alter a plant’s morphology at the cellular, tissue, and organ levels. When nanoparticles come into contact with plant tissues, they induce changes that can enhance the plant’s general morphology and growth characteristics. For instance, modification in root and shoot growth can occur. Nanoparticles

influence the architecture of the roots and shoots, leading to aberrant branching patterns, elongation, or stunted growth. The extent of root branching and shoot growth rate may vary by nanoparticle type and amount. Modifications of leaf morphology, such as changes in leaf size, texture, and form, can also be influenced by nanoparticles. Research indicates that nanoparticles impact stomatal density, leaf curvature, and the development of thicker or thinner cuticles on the leaf surface. At the cellular level, nanoparticles can alter cell morphology, affecting cell size, division, and wall thickness (Wu & Li, 2022).

Changes in leaf or stem anatomy indicate alterations in the general structure of plant components. Nanoparticles can accumulate in plant roots, leaves, or vascular tissues, causing noticeable changes like discoloration or abnormal tissue formation. Stress responses triggered by nanoparticle exposure can also result in morphological changes in plants, affecting biomass, height, and protective structure development. Nano-fertilization is becoming popular for improving crop performance, with a study focusing on soybean growth using different nanoparticles. Fe_2O_3 and “fulvic-acid = coated” (Fe_2O_3 -FA) positively increase biomass and root growth of plants, and chlorophyll content without toxicity, in contrast with the traditional method (Fe-EDTA). Foliar application of nanoparticles increased shoot iron content compared to soil application, with only Fe_2O_3 -FA promoting nitrogen fixation. The discovery also led to increased potassium and zinc uptake in plants. As an ensemble, Fe_2O_3 -FA was more effective than Fe_2O_3 alone in stimulating soybean growth. It is crucial to consider phosphorus availability and interactions, as treatments decreased P concentration in plants and soil under Fe_2O_3 amendment, potentially causing P deficiency in acidic soils (Yang et al., 2020). Another study investigated the use of neem leaf extra (*Azadirachta indica*) as a readily accessible resource to synthesize silver nanoparticles. To study its impact on tomato seedling development and germination, the *A. indica* plant was used as a reducing particle size, capping, and coating agent. Adding 10 ml of 1 ml silver nitrate to 10 ml Neem plant extract resulted in the maximum produced silver nanoparticles after 3 h at 70 °C. It also examined how solvent type and extract preparation affected plant-based-silver nanoparticle production. Silver nanoparticles of 22–30 nm size were synthesized and stabilized with functional groups like ethylene, amide, carbonyl, methoxy, alcohol, and phenol. Treated tomato seeds showed a 70% higher germination rate and shorter germination time. Shoot length increased by 25–80%, fresh biomass by 10–80%, and root length by 10–60% with soluble sugar, protein, carotene, flavonoids, and total chlorophyll output significantly raised (Ansari et al., 2023). Fabricated copper-based nanoparticles lead to raised drought tolerance of maize plants and increased biomass, leaf water content, chlorophyll, anthocyanin, and carotenoid levels with reduced ROS accumulation. However, Histological tests with NBT and 3,3'-diaminobenzidine revealed decreased accumulation of reactive oxygen species in plants due to enhanced enzyme activity under drought. The application of copper nanoparticles during drought improved total seed count and grain output. These findings suggest that copper nanoparticles can regulate plant defense systems against drought, providing a promising method for developing drought-resistant crop plants (Van Nguyen et al., 2022). On the Contrary, Barley roots responded to gold

nanoparticles at different concentrations, showing morphological, histological, and ultra-structural changes without penetration, such as reddish coloration, increased root diameter, rhizodermal cell damage, and reduced root hair cell production (Milewska-Hendel et al., 2022).

11.5 Metal-Based Nanomaterials and Their Physiological Responses on Plants

11.5.1 Effects of Nanoparticles on Enzymes

An exciting discovery is the way nanoparticles can modulate a plant's antioxidant defense system as shown in Fig. 11.3. The activity of reactive oxygen species (ROS) decreased as a result of the increased levels of essential antioxidant enzymes such as

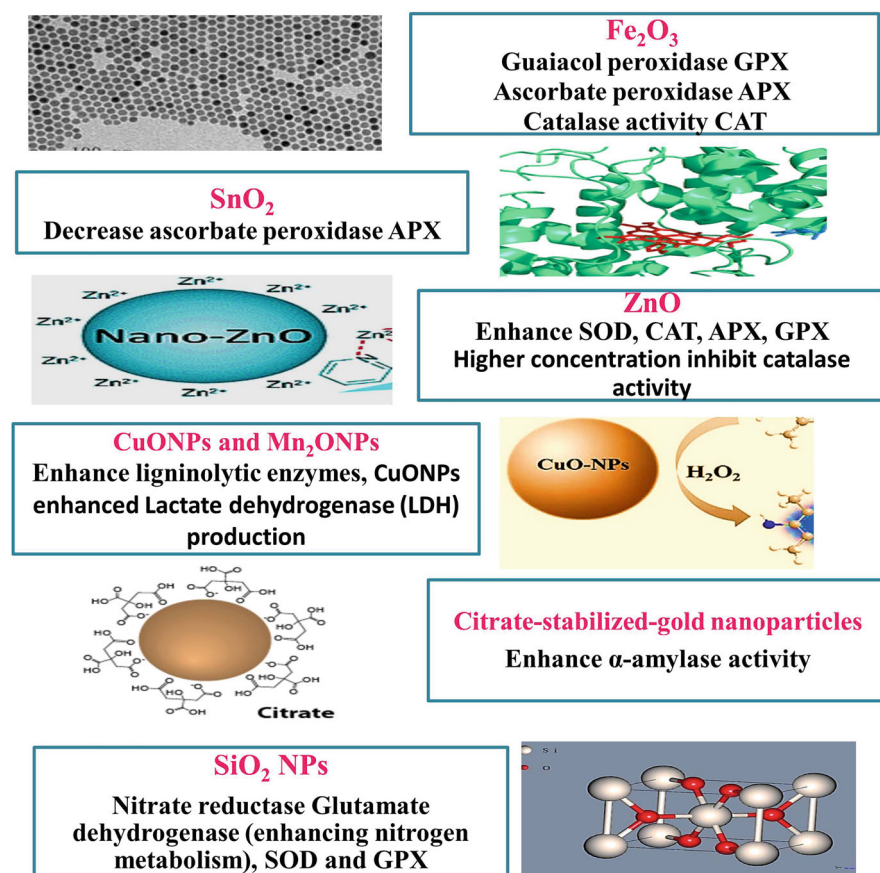


Fig. 11.3 The impact of nanoparticles on plant's defense system (enzymes)

guaiacol peroxidase, catalase, and ascorbate peroxidase in *brassica juncea* after treatment with silver nanoparticles. Similarly, gold nanoparticles occurred to enhance the activity of enzymes such as catalase, superoxide dismutase, guaiacol peroxidase, ascorbate peroxidase, and glutathione reductase, while also increasing H_2O_2 and proline content. Nanoparticles (NPs) significantly influence enzyme activity in plant cells, affecting biochemical pathways and physiological responses. Their interactions with enzymes can lead to both beneficial and detrimental effects, subject to a variety of factors including size, concentration, and type of NP. Nanoparticles can adsorb onto enzymes, altering their activity by mimicking substrate interactions or inhibiting catalytic functions (Alabdallah & Kotb, 2024). Which activates antioxidant enzymes like superoxide dismutase and catalase, crucial for mitigating reactive oxygen species (ROS) damage. Nanoparticles can act as reactive oxygen species activators or scavengers, impacting enzymes in plant cells. Nanozymes play a role in antioxidant systems, affecting biochemical reactions in plants. Nanoparticles like Fe_2O_3 and Al_2O_3 affect antioxidant enzymes in wheat seedlings differently; Fe_2O_3 increases ascorbate peroxidase activity (APX), while Al_2O_3 increases enzyme activity with concentration. Additionally, Fe_2O_3 nanoparticles increase guaiacol peroxidase (GPOX), and catalase activity (CAT) in plant cells, while SnO_2 decreases APX and GPOX but increases CAT activity (Ismailova & Azizov, 2022; Raj et al., 2024). Additionally, Nanoparticles like ZnO NPs can increase antioxidant enzyme activities (SOD, CAT, APX, GPX) in plant cells, promoting plant growth and stress tolerance (Srivastav et al., 2023). Silica nanoparticles (SiO_2 NPs) at 300 ppm via foliar spray enhance enzyme activity in *Dianthus caryophyllus* L. plants, promoting growth, bioactive compounds, and anatomical structure compared to drench application (El-Sayed & Soliman, 2024). Nanoparticles regulate enzymes like nitrate reductase and glutamate dehydrogenase in plant cells, enhancing nitrogen metabolism. They also upregulate genes like SOD and GPX for stress tolerance (Ghosh & Bera, 2021). Nanoparticles like Mn_2ONPs and $CuONPs$ enhance ligninolytic enzymes (CMCase, FPase, Laccase, MnPase) activity in *Phanerochaete chrysosporium*, improving productivity levels at specific concentrations (Al-Rajhi et al., 2024). While, silver nanoparticles inhibit soil enzyme activities in wetland plant rhizospheres, with higher concentrations showing more significant effects. Lower levels impact enzyme activities based on plant species (Cao et al., 2017). Metal-based nanoparticles like Cu, Ni, and Zn affect enzyme activity in plant cells. Copper nanoparticles have a positive effect on lactate dehydrogenases (LDH). While, NiNPs and ZnNPs inhibit catalase activity (Kolesnikov et al., 2021). Whereas, nanoparticles like CeO_2 have both activated and reduced enzyme activity in plants. For example, CeO_2 at lower concentrations enhances catalase activity but decreases it at higher concentrations (Siddiqi & Husen, 2017). Furthermore, Citrate-stabilized-gold nanoparticles enhance α -amylase activity by influencing enzymatic activities, exhibiting higher activity at smaller nanoparticle concentrations, but higher levels lead to protein agglomeration effects in plant cells (Deka et al., 2012).

11.5.2 Effects of Nanoparticles on Hormones

The influence of mineral nanomaterials on plant hormones such as auxins and cytokinins is significant, with effects varying by type and concentration of nanoparticles. Research indicates that these nanomaterials can enhance plant growth, including root and branch development, through hormonal modulation. Different nanoparticles, like SiO₂ and MnO₂, have been shown to increase growth parameters significantly, while ZnO-NPs can negatively impact growth at higher concentrations. Additionally, the application of SiO₂-NPs up-regulated genes related to auxin and cytokinin, suggests a direct influence on hormonal pathways that promote growth (Zhang et al., 2024). Nanomaterials can modulate the balance of phytohormones, as seen with nano-pyrite, which increased the anthocyanin and gibberellic acid to abscisic acid ratio, impacting increased seed germination and 25.46% increase in yield of mature red radishes (Kaler et al., 2024). Mineral nanoparticles can influence plant hormones like auxins and cytokinins, affecting root growth, side branches, and blooms. Effects vary based on nanoparticle type and concentration (Sarmast et al., 2023). Metal nanomaterials boost metal homeostasis, particularly zinc and iron, influencing hormone-related immune responses. Carbon nanomaterials act as signaling amplifiers, alleviating water deprivation and enhancing growth responses in plants (Wu et al., 2024). The Arabidopsis study shows that nanoparticles can impact plant hormones like salicylic acid, affecting root hair development and defense responses, and potentially influencing root growth and branching (García-Sánchez et al., 2021). Nanoparticles of biogenic ferrihydrite enhanced root formation in Ledebour willow cuttings by increasing free radicals and Mn²⁺ cleavage, impacting root development and superoxide dismutase activity (Bopp et al., 2018).

11.5.3 Gas Exchange and Element Absorption

Nanoparticle treatment enhances gas exchange and element absorption in biological systems through several mechanisms, primarily involving their unique physical and chemical properties including type, pH, size, concentration, temperature, and pressure (Meshksar et al., 2022). These mechanisms include improved transport dynamics, enhanced solubility, and interactions with cellular structures. The use of nanofluids has been shown to improve gas absorption by increasing the kinetics of gas component capture and reducing the energy required for solvent regeneration (Meshksar et al., 2022). Nanoparticles can modulate ROS levels, which may influence cellular respiration and gas exchange processes (Rawat et al., 2021). Nanoparticles can be transported between cells via extracellular vesicles (EVs), facilitating their delivery and enhancing their biological effects (Garcés et al., 2021). This mechanism allows for efficient intercellular communication and nutrient absorption. The size, shape, and concentration of nanoparticles significantly affect their interaction with biological systems, impacting their efficacy in promoting

element absorption and gas exchange. The enhancement mechanisms of mass transfer performance by nano-absorbents during the CO₂ absorption process include increased surface area, improved solubility, and enhanced reaction kinetics, facilitating gas exchange and element absorption (Li & Kang, 2021). While these mechanisms highlight the benefits of nanoparticle treatment, it is important to be conscious of the potential toxicity and negative effects associated with its application, because it can cause oxidative stress and deterioration of the biological system. (Rawat et al., 2021). The intercellular exchange of nanoparticles involves exocytosis and re-entry via extracellular vesicles, showing the significant contribution to nanoparticle transport within and between cells for enhanced biological effects (Wu et al., 2022).

11.5.4 The Molecular-Level Changes Induced by Nanoparticle Treatments and Their Functional Implications for Plant Physiology and Responses

At the molecular level, Nanoparticle treatment has been shown to up-regulate several specific genes involved in oxidative stress defense across different biological systems (Table 11.1). Zhang et al. (2024) found that after 48 h, SOD expression increased fourfold, but CAT and GS expression elevated sixfold in response to SiO₂ nanoparticles. *Arabidopsis thaliana* exhibited a pronounced oxidative stress response following exposure to cerium oxide (CeO₂) nanoparticles, evidenced by increased activities of superoxide dismutase (SOD), catalase (CAT), Ascorbate peroxidase (APX), and peroxidase (POD). Moreover, there was significant elevation in the activities of glutathione reductase (GR) and glutathione S-transferase (GST) (Pathak et al., 2023). These findings indicate the essential function of these genes in regulating oxidative stress defense mechanisms in reaction to nanoparticle exposure. The effect of silver nanoparticles (AgNPs) on gene expression in response to metal and oxidative stress has been studied in *Arabidopsis thaliana*. Specifically, AgNPs treatment has been shown to up-regulate genes involved in oxidative stress defense while down-regulating those associated with plant defense mechanisms, auxin regulation, and ethylene signaling pathways (Pathak et al., 2023). This suggests that AgNPs can profoundly influence a plant's genetic and metabolic pathways, potentially enhancing stress tolerance and nutrient uptake (Francis et al., 2024). Furthermore, the interaction of AgNPs with plant cells can lead to physiological disruptions, including reduced photosynthesis and growth, which may impact overall crop productivity (Noori et al., 2024). While these findings highlight the potential of AgNPs in precision agriculture and crop enhancement, concerns regarding their phytotoxicity and environmental impact necessitate careful consideration and further research to ensure sustainable application in agricultural practices (Santhoshkumar et al., 2024). Nanoparticle treatment has been shown to up-regulate several specific genes across different studies, with functional implications varying by cell type and

Table 11.1 Physiological and molecular-level changes in plants in response to nanoparticle exposure

Nanoparticle type	Effects on physiological parameters and plant growth.	Molecular-level changes	References
Silver NPs	Enhance overall growth, chlorophyll content	Enhanced the expression of genes involved in glycoside biosynthesis like UGT85C2, KAH, UGT74G1, and UGT76G1.	Ramezani et al. (2020)
Titanium	Increase root and shoot growth. Enhance nutrient uptake.	Up-regulate genes that respond to stress include ABA and SA signaling pathways. Gene related to nutrient uptake such as those involved in phosphate and iron acquisition.	Pathak et al. (2023)
Copper	Improved seed germination. Increase biomass. Help plants manage oxidative stress.	Up-regulate genes involve in the process of antioxidant defense, catalase (CAT), peroxidase (POD), and superoxide dismutase (SOD).	Pathak et al. (2023)
Zinc NPs	Increase root length and improve photosynthesis efficiency.	Up-regulate stress-related genes and increase production of ROS, increase the expression of superoxide catalase (CAT), dismutase (SOD), and glutamine synthetase (GS) in HT-29 colon adenocarcinoma cells.	Zhang et al. (2024)
Gold NPs	Enhance growth, and increase chlorophyll content. Increase antioxidant activity.	Up-regulation of transcription factors such as Myb, WRKY, NAC, ERF, and bHLH, which are involved in growth, antioxidant potential, hormonal regulation, and stress responses.	Joshi and Joshi (2024)
SiO ₂ -NPs		SiO ₂ -NPs up-regulated genes related to photosystem activities and hormone signaling, particularly auxin and cytokinin pathways.	Zhang et al. (2024)
cerium oxide (CeO ₂) nanoparticles	Influence both root and shoot growth modulating oxidative stress.	Up-regulate genes involved in antioxidant defense include CAT, SOD, ascorbate peroxidase (APX), and peroxidase (POD). Additionally, glutathione S-transferase (GST) and glutathione reductase (GR) activities were also significantly increased. Genes related to stress tolerance such as heat shock proteins And down-regulate at higher concentrations CeO ₂ can down-regulate genes involved in photosynthesis and genes associated with cell division and growth.	Pathak et al. (2023)

nanoparticle composition. For instance, plants exposed to AgNPs significantly enhanced the expression of genes involved in glycoside biosynthesis, such as UGT85C2, indicating a potential for increased production of beneficial compounds like stevioside (Ramezani et al., 2020). These findings represent the diverse biological responses elicited by nanoparticle treatments, emphasizing the need for careful evaluation of their safety and efficacy in various applications. Nanoparticle treatments in plants have been shown to up-regulate various genes with significant functional implications. For instance, in *Nardostachys jatamansi*, treatment with CTAB-AuNPs led to the up-regulation of transcription factors such as Myb, WRKY, NAC, ERF, and bHLH, which are involved in growth, antioxidant potential, hormonal regulation, and stress responses (Joshi & Joshi, 2024). Similarly, in *Stevia rebaudiana*, silver nanoparticles enhanced the expression of key biosynthetic genes like UGT85C2, KAH, UGT74G1, and UGT76G1, crucial for glycoside production (Ramezani et al., 2020). Furthermore, in *Cyclocarya paliurus*, SiO₂-NPs up-regulated genes related to photosystem activities and hormone signaling, particularly auxin and cytokinin pathways (Zhang et al., 2024). These findings suggest that nanoparticle treatments can modulate gene expression related to growth, stress response, and metabolic pathways, although the extent of these effects can vary based on the type and concentration of nanoparticles used (García-Sánchez et al., 2021; Ghosh & Bera, 2021). Genes that control plant defenses, auxin levels, and ethylene signaling pathways that are turned down greatly enhance growth. Auxin is an essential plant hormone that activates defense genes in response to environmental challenges and pathogen infections. Absciscic acid is one of the hormones with which it interacts to regulate growth and defense responses. The nuclear pyruvate dehydrogenase complex mediates ethylene signaling, which is essential for stress and development (Shao et al., 2024). Furthermore, Auxin affects gene expression through transcription factors and microRNAs, highlighting its role in plant adaptation to varying conditions (Pathak et al., 2023).

11.6 The Uptake and Accumulation

The uptake and accumulation of nanoparticles in plants involve complex mechanisms influenced by the nanoparticles' properties and the specific plant species. Research indicates that nanoparticles can be absorbed through both leaves and roots, with factors such as particle size, shape, surface chemistry, and concentration significantly affecting their uptake and translocation within plant systems (Noori et al., 2024). For instance, metal and metal oxide nanoparticles exhibit both beneficial and harmful effects, impacting seed germination, growth, and biochemical processes (Javed et al., 2024). Additionally, excessive concentrations can lead to phytotoxicity, disrupting physiological functions and inducing oxidative stress (Gowtham et al., 2024). The interaction mechanisms are nuanced, with nanoparticles potentially associating with cell membranes and organelles, leading to toxic ion release and reactive oxygen species generation (Gowtham et al., 2024). Furthermore,

innovative delivery methods and detection techniques are essential for optimizing nanoparticle transport and understanding their localization within plant tissues (Sembada & Lenggoro, 2024).

Overall, the interplay between nanoparticles and plants is multifaceted, necessitating further research to elucidate these mechanisms fully (Emamverdian et al., 2024). Additionally, the interaction of nanoparticles with plant systems can lead to various physiological and morphological changes, which may be harnessed to improve plant growth and defense mechanisms (Ahmad et al., 2023). Nanoparticle-based delivery systems are also being developed to facilitate the internalization of genetic material, enhancing genetic engineering efforts in plants (Yong et al., 2024). However, while these advancements show promise, there are concerns regarding the environmental impacts and potential toxicity of engineered nanoparticles ENPs on both cultivated and wild plant species, highlighting the need for further research to understand these interactions fully (Wojcieszek & Ruzik, 2022; Marchiol et al., 2022). Thus, while engineering plants for nanoparticle uptake is feasible, careful consideration of ecological implications is essential. The research demonstrates that pumpkin plants can naturally uptake and accumulate iron oxide nanoparticles, suggesting potential for engineering plant species for targeted nanoparticle uptake in specific applications. Plant species like *Brassica juncea* can accumulate gold nanoparticles, showing potential for uptake. Further research is needed to optimize this process for specific applications like catalysis (Natarajan et al., 2024).

11.6.1 Foliar and Root Application

Application of nanoparticles for both foliar and root can improve plant defenses and productivity. Further investigations are required to maximize environmental parameters and absorption systems for particular uses of engineered nanoparticles. Additionally, understanding the interactions between nanoparticles and plant physiology will be crucial for developing effective strategies. Engineered nanoparticle formulations in agriculture can optimize benefits and minimize risks. Long-term effects on soil health and microbial communities must be explored for sustainable practices. Bioaccumulation in food crops needs investigation for safety and ecological balance. Collaboration across disciplines is crucial for advancing nanotechnology in farming (Hong et al., 2021). Nanoparticles are absorbed differently in roots and leaves, with roots using symplastic and apoplastic pathways (The negatively charged cell walls attract positively charged nanoparticles, allowing them to accumulate on the surface but not always enter the tissue), and leaves absorbing through stomata, where the size and surface charge of nanoparticles influence their accumulation and transport to the vascular system (Wang et al., 2023), such as selenium, silver, copper, and ceria can be applied to leaves for antioxidant and antimicrobial benefits. They pass through leaf parenchyma, aiding plant physiology and development (Roy, 2023).

In roots, nanoparticles can be transported radially or enter the vascular system at lateral root junctions. While in leaves, nanoparticles that enter can be transferred to the vascular bundles, and then to the roots, with negatively charged nanoparticles showing better transfer efficiency. Nanoparticles can impact root growth and nutrient absorption, as well as affect photosynthesis and overall plant health (Wang et al., 2023). **Titanium Dioxide (TiO₂) Nanoparticles:** These are often favored for foliar applications due to their ability to enhance photosynthesis and improve plant growth. TiO₂ nanoparticles can penetrate leaf tissues effectively, promoting better light absorption and energy conversion during photosynthesis (Akram et al., 2024; Wang et al., 2023). Meanwhile, ZnO nanoparticles are also popular for foliar application as they can stimulate plant growth and enhance resistance to pathogens. Their small size allows for easy absorption through leaf stomata, making them effective in improving overall plant health (Dangana et al., 2023; Wang et al., 2023). **Copper Oxide (CuO) Nanoparticles** are commonly used in root applications due to their ability to improve nutrient uptake and stimulate root growth. However, they can be toxic at high concentrations, which necessitates careful management of their application (El-Abeid et al., 2024). **Zinc Oxide (ZnO) Nanoparticles** are similar to their use in foliar applications, ZnO nanoparticles are also effective in root applications. They can enhance nutrient absorption and improve the antioxidant capacity of plants, helping them cope with stress conditions (Wang et al., 2023). The choice of nanoparticles for foliar or root application is influenced by their size, surface charge, and chemical composition, which affect their absorption and transport mechanisms in plants. For instance, smaller nanoparticles tend to penetrate tissues more easily, while surface charge can determine how well they interact with plant cells. Additionally, the physiological effects of nanoparticles, such as promoting growth or enhancing stress resistance, play a crucial role in their selection for specific applications. The ability to improve nutrient uptake and overall plant health makes certain nanoparticles more favorable for root applications, while others are better suited for enhancing photosynthesis and leaf health in foliar applications (Nazeer et al., 2023; Wang et al., 2023).

11.6.2 Application of Nanoparticles on Fruit

Fruit production is a Major of global agriculture, providing essential nutrients and contributing to food security. However, fruit crops are susceptible to a wide range of diseases caused by pathogens, such as fungi, bacteria, and viruses, which can significantly reduce yield and quality. Traditional disease management strategies often rely on the use of synthetic fungicides, which can have adverse effects on the environment and health (Shi et al., 2024). In recent years, there has been increasing interest in exploring alternative approaches, including nano- and biocontrol strategies, to manage fruit diseases in a more sustainable and environmentally friendly manner. Improving the antifungal properties of specific fruit species and fungal strains using nanomaterials has been the subject of recent research. Nanocomposites, which combine nanoparticles and polymers, can be designed to deliver antifungal

agents in a targeted manner, enhancing their efficacy while minimizing environmental impact and resistance development (Rameez et al., 2024; Shi et al., 2024). Studies have shown that the efficacy of antifungal composite materials, such as polyurethane with silver nanoparticles, can be improved by modifying parameters such as nanoparticle size and concentration. Improved antifungal properties of PUR/AgNPs composite against *Trichophyton rubrum* (Mares Castro et al., 2023). The development of nano-fungicides also highlights the potential for site-specific applications, which can improve efficacy against resistant strains while reducing overall pesticide use (Srivastava et al., 2024). Overall, the integration of nanotechnology into fungal control strategies represents a promising avenue for improving disease management in agriculture, especially for specific fruit species and fungal challenges (Zhu et al., 2024).

11.6.2.1 Nanoparticle-Based Fungicides

Metal-based nanoparticles, including silver, copper, and zinc oxide, exhibit significant beneficial effects against several fruit diseases. These nanoparticles may attack fungal cell membranes, produce reactive oxygen species, and disturb essential cellular processes, resulting in the suppression of fungal growth and development. Nanoparticles may boost the absorption and effectiveness of traditional fungicides, supporting reduced application rates and improved disease management (Xu et al., 2021).

11.6.2.2 Nanomaterial-Based Delivery Systems

Polymeric nanoparticles, liposomes, and dendrimers, which are nanomaterial-based carriers, can be employed to encapsulate and deliver antifungal agents, thus improving their solubility, stability, and targeted delivery to the infection site. These nanomaterial-based delivery systems can enhance bioavailability and improve the controlled release of active compounds, leading to more effective and long-lasting disease management. Nanomaterial-based biosensors can be developed to rapidly detect and monitor the presence of pathogens in fruits, enabling early intervention and prevention of disease outbreaks (Chaudhari et al., 2024; Cruz-Luna et al., 2021). These biosensors can utilize different detection principles, such as optical, electrochemical, or surface-enhanced Raman scattering, to provide sensitive and specific identification of target pathogens (Zhao et al., 2018).

11.7 Compare the Efficacy of Nanomaterial with Fungicides and Investigate Their Mode of Action

Engineered nanoparticles possess the ability to transform interact with and utilization of plants. The special features of nanoparticles, including their small size, large surface area, and catalytic qualities, enable them to interact with plants at the

molecular level in unique directions. Metal-based nanoparticles, particularly copper oxide (CuO), silver (AgNPs), and zinc oxide (ZnO) nanoparticles, have emerged as effective agents for controlling plant diseases due to their antimicrobial properties. CuO nanoparticles have demonstrated significant efficacy in inhibiting the growth of the *Pythium ultimum* isolate, outperforming *Pythium aphanidermatum*, indicating their potential as a robust pesticide formulation for agricultural use (Ashraf et al., 2021). Similarly, silver nanoparticles are recognized for their antifungal activity and are widely utilized in managing diseases in various crops like wheat and barley (Kashyap et al., 2022). ZnO nanoparticles also exhibit antifungal effects, although their impact is less lethal compared to CuO, as they induce stasis in pathogen growth rather than complete inhibition (Dimkpa, 2014).

The interaction of these nanoparticles with plant pathogens involves mechanisms that disrupt cellular functions, leading to pathogen death or growth inhibition. Additionally, the biosynthesis of these nanoparticles using fungi enhances their effectiveness and eco-friendliness, providing a sustainable alternative to traditional chemical pesticides. The antifungal activity of metal-based nanomaterials, particularly copper oxide nanoparticles (CuO-NPs), has been increasingly recognized for their potential in modulating plant-microbe interactions. Research indicates that CuO-NPs exhibit significant antifungal effects against various phytopathogens, such as *Fusarium oxysporum* and *Botrytis cinerea*, often in combination with traditional fungicides, enhancing their efficacy while reducing environmental impact (Parada et al., 2024). For instance, CuO-NPs derived from *Zizyphus spina* leaf extract demonstrated a disease reduction of 72.0% to 88.6% against *Fusarium* root rot in tomatoes, highlighting their effectiveness in agricultural applications (El-Abeid et al., 2024). Additionally, the biogenic synthesis of metal nanoparticles using fungi like *Trichoderma harzianum* has shown promising antifungal activity without adversely affecting seed germination. The mechanisms of action primarily involve the generation of reactive oxygen species (ROS), which disrupt fungal cellular integrity. Overall, metal-based nanomaterials represent a sustainable and effective strategy for enhancing plant health and managing fungal diseases in agriculture. However, the impact of nanoparticles on plants remains under investigation, however, early findings have been encouraging (Castro-Longoria, 2022; Lyagin et al., 2023). The efficacy of nanomaterials in agricultural applications, particularly when compared with traditional fungicides, receives considerable interest owing to their special properties and modes of action. Nanomaterials, such as engineered nanoparticles, have demonstrated potential effectiveness in managing pests and diseases compared to conventional fungicides. For example, highlights that engineered nanomaterials can enhance the efficiency of agricultural practices while alleviating environmental impacts, suggesting that these materials may outperform their traditional counterparts in certain contexts (De La Torre-Roche et al., 2020). Similarly, notes that copper-based nanoparticles can increase the effectiveness of copper-based fungicides, suggesting a synergistic potential that could lead to improved disease control in crops (Hamers, 2017).

The mode of action of nanomaterials differs from that of traditional fungicides. Traditional fungicides typically act by disrupting cellular processes in fungi, such as

inhibiting cell wall synthesis or interfering with nucleic acid synthesis. In contrast, nanomaterials can exert their effects through multiple mechanisms, including the generation of reactive oxygen species (ROS), which can lead to oxidative stress in microbial cells (Alimohammadi et al., 2018). For example, the antibacterial properties of two-dimensional 2D nanomaterials such as Ti_3C_2 MXene are attributed to their ability to disrupt bacterial membranes and induce oxidative damage (Shamsabadi et al., 2018). This multifaceted mode of action allows nanomaterials to target pathogens more effectively and may reduce the likelihood of resistance developing, a major concern with conventional fungicides (Al-Zaban et al., 2022).

Furthermore, the unique physical and chemical properties of nanomaterials, such as their high surface area and reactivity, enable them to interact with pathogens in ways that conventional fungicides cannot. Furthermore, the small size of 2D nanomaterials allows them to penetrate bacterial cells more easily, facilitating the release of metal ions that can disrupt cellular functions (Alimohammadi et al., 2018). This contrasts with conventional fungicides, which may not penetrate as effectively or may require higher concentrations to achieve similar effects. In terms of environmental impact, nanomaterial also offers advantages over conventional fungicides. They can be designed to reduce toxicity to non-target organisms and reduce the overall chemical load in agricultural systems (Al-Zaban et al., 2022; Jasrotia et al., 2022). This is particularly important in the context of sustainable agriculture where the goal is to maintain productivity while minimizing harmful environmental impacts. For example, synthesized zinc oxide nanoparticles have been shown to enhance systemic antibacterial efficacy against plant diseases while being less harmful to beneficial organisms (Soliman et al., 2022). In summary, comparing nanomaterials and conventional fungicides reveals that nanomaterials not only offer enhanced efficacy but also offer various multifaceted mechanisms of action. Their ability to generate reactive oxygen species, penetrate microbial cells, and reduce environmental toxicity makes them alternatives promising in agricultural pest and disease management.

11.8 Conclusion

In recent years, nanotechnology has been considered a fruitful alternative to protect plants from various biotic stresses. Due to their small size, nanomaterials exhibit features that significantly differ from those of their bulk counterparts. This improves the efficacy of the materials, however they pose minimal risk and are environmentally friendly. Although nanotechnology presents interesting possibilities, it is essential to evaluate the potential advantages and disadvantages. Comparing nanomaterials and conventional fungicides reveals that nanomaterials not only offer enhanced efficacy but also offer various multifaceted mechanisms of action. Their ability to generate reactive oxygen species, penetrate microbial cells, and reduce environmental toxicity makes them alternatives promising in agricultural pest and disease management. Additionally, efforts should focus on sustainable

and safe nanotechnology methods to improve food production while reducing the incidence of diseases and pests in plants. Nanotechnology can enhance methods for early detection of plant diseases. Using nanosensors or other nanomaterial-based technologies, we can identify pathogens at an early stage, allowing timely intervention.

References

- Ahmad, S., Pathak, A. K., Minj, R. P., Chaudhary, S., Kumar, A., Chalotra, T., & Raina, N. (2023). A comprehensive review of nanoparticles induced stress and toxicity in plants. *Universal Journal of Green Chemistry*, 1, 18–43.
- Akram, W., Mia, R., Ullah, S., Assiri, M. A., & Fang, J. (2024). Simultaneous synthesis and application of TiO₂ nanoparticles using mulberry leaves for functionalization of organic cotton fabric. *Journal of Cleaner Production*, 440, 140939.
- Alabdallah, N. M., & Kotb, E. (2024). Nanoparticles: Unveiling the impact on biochemical reactions in plants. In *Molecular impacts of nanoparticles on plants and algae* (pp. 195–209). Academic.
- Ali, F., Mehmood, S., Ashraf, A., Saleem, A., Younas, U., Ahmad, A., et al. (2023). Ag–Cu embedded SDS nanoparticles for efficient removal of toxic organic dyes from water medium. *Industrial & Engineering Chemistry Research*, 62(11), 4765–4777.
- Alimohammadi, F., Sharifian Gh, M., Attanayake, N. H., Thenuwara, A. C., Gogotsi, Y., Anasori, B., & Strongin, D. R. (2018). Antimicrobial properties of 2D MnO₂ and MoS₂ nanomaterials vertically aligned on graphene materials and Ti₃C₂ MXene. *Langmuir*, 34(24), 7192–7200.
- Al-Rajhi, A. M., Alharbi, A. A., Alsalamah, S. A., & Abdelghany, T. M. (2024). Nanoparticles enhanced Ligninolytic enzymes activity of rotten wood fungus *Phanerochaete chrysosporium*. *BioResources*, 19(2), 2371–2382.
- Al-Zaban, M. I., Alhag, S. K., Dabloul, A. S., Ahmed, A. E., Alghamdi, S., Ali, B., et al. (2022). Manufactured nano-objects confer viral protection against cucurbit chlorotic yellows virus (CCYV) infecting *nicotiana benthamiana*. *Microorganisms*, 10(9), 1837.
- Ameen, F., Alsamhary, K., Alabdullatif, J. A., & ALNadhari, S. (2021). A review on metal-based nanoparticles and their toxicity to beneficial soil bacteria and fungi. *Ecotoxicology and Environmental Safety*, 213, 112027.
- Ansari, M., Ahmed, S., Abbasi, A., Khan, M. T., Subhan, M., Bukhari, N. A., et al. (2023). Plant mediated fabrication of silver nanoparticles, process optimization, and impact on tomato plant. *Scientific Reports*, 13(1), 18048.
- Ashraf, H., Anjum, T., Riaz, S., Ahmad, I. S., Irudayaraj, J., Javed, S., et al. (2021). Inhibition mechanism of green-synthesized copper oxide nanoparticles from *Cassia fistula* towards *Fusarium oxysporum* by boosting growth and defense response in tomatoes. *Environmental Science: Nano*, 8(6), 1729–1748.
- Azadi, S., Azizpour, E., Amani, A. M., Vaez, A., Zareshahrbadi, Z., Abbaspour, A., et al. (2024). Antifungal activity of Fe₃O₄@ SiO₂/Schiff-base/Cu (II) magnetic nanoparticles against pathogenic *Candida* species. *Scientific Reports*, 14(1), 5855.
- Bharathi, D., Ranjithkumar, R., Vasantharaj, S., Chandarshekar, B., & Bhuvaneshwari, V. (2019). Synthesis and characterization of chitosan/iron oxide nanocomposite for biomedical applications. *International Journal of Biological Macromolecules*, 132, 880–887.
- Bopp, V. L., Mistratova, N. A., Petrakovskaya, E. A., Gurevich, Y. L., Teremova, M. I., & Khlebopros, R. G. (2018). The influence of nanoparticles of biogenic ferrihydrite on the rooting of lignified cuttings of the ledebour willow. *Biophysics*, 63, 621–628.

- Cao, C., Huang, J., Cai, W. S., Yan, C. N., Liu, J. L., & Jiang, Y. D. (2017). Effects of silver nanoparticles on soil enzyme activity of different wetland plant soil systems. *Soil and Sediment Contamination: An International Journal*, 26(5), 558–567.
- Castro-Longoria, E. (2022). Biosynthesis of metal-based nanoparticles by trichoderma and its potential applications. In *Advances in Trichoderma biology for agricultural applications* (pp. 433–463). Springer International Publishing.
- Chaudhari, V., Vairagade, V., Thakkar, A., Shende, H., & Vora, A. (2024). Nanotechnology-based fungal detection and treatment: Current status and future perspective. *Naunyn-Schmiedeberg's Archives of Pharmacology*, 397(1), 77–97.
- Chauhan, D., Talreja, N., & Ashfaq, M. (2024). Biogenic nanofungicides: Next-generation antimicrobial materials. In *Nanofungicides* (pp. 51–64). Elsevier.
- Cruz-Luna, A. R., Cruz-Martínez, H., Vásquez-López, A., & Medina, D. I. (2021). Metal nanoparticles as novel antifungal agents for sustainable agriculture: Current advances and future directions. *Journal of Fungi*, 7(12), 1033.
- Dangana, R. S., George, R. C., Shittu, U. O., & Agboola, F. K. (2023). Facile biosynthesis, characterisation and biotechnological application of ZnO nanoparticles mediated by leaves of *Cnidioscolus aconitifolius*. *Artificial Cells, Nanomedicine, and Biotechnology*, 51(1), 309–317.
- De La Torre-Roche, R., Cantu, J., Tamez, C., Zuverza-Mena, N., Hamdi, H., Adisa, I. O., et al. (2020). Seed biofortification by engineered nanomaterials: A pathway to alleviate malnutrition? *Journal of Agricultural and Food Chemistry*, 68(44), 12189–12202.
- Deka, J., Paul, A., & Chattopadhyay, A. (2012). Modulating enzymatic activity in the presence of gold nanoparticles. *RSC Advances*, 2(11), 4736–4745.
- Dimkpa, C. O. (2014). Can nanotechnology deliver the promised benefits without negatively impacting soil microbial life? *Journal of Basic Microbiology*, 54(9), 889–904.
- El-Abeid, S. E., Mosa, M. A., El-Tabakh, M. A., Saleh, A. M., El-Khateeb, M. A., & Haridy, M. S. (2024). Antifungal activity of copper oxide nanoparticles derived from *Zizyphus spina* leaf extract against *Fusarium* root rot disease in tomato plants. *Journal of Nanobiotechnology*, 22(1), 28.
- Elkhodary, B. H., Attia, M. S., El-Sayyad, G. S., & Salem, M. S. (2023). Effectiveness of bimetallic ZnO-B₂O₃ nanoparticles produced by *Streptomyces gancidicus* as prospective antifungal agents and therapeutic nutrients to enhance pea plant immunity against damping off-causing *Pythium* irregular: In vivo and in vitro investigations. *Biomass Conversion and Biorefinery*, 15, 1–24.
- El-Sayed, I. M., & Soliman, D. M. (2024). Silica nanoparticles improve growth, chemical bioactive, and antioxidant enzyme activity of *Dianthus caryophyllus* L., plant. *Egyptian Pharmaceutical Journal*, 23, 279–289.
- Emamverdian, A., Khalofah, A., Pehlivan, N., Li, Y., Chen, M., & Liu, G. (2024). Iron nanoparticles in combination with other conventional Fe sources remediate mercury toxicity-affected plants and soils by nutrient accumulation in bamboo species. *Ecotoxicology and Environmental Safety*, 278, 116431.
- Francis, D. V., Abdalla, A. K., Mahakham, W., Sarmah, A. K., & Ahmed, Z. F. (2024). Interaction of plants and metal nanoparticles: Exploring its molecular mechanisms for sustainable agriculture and crop improvement. *Environment International*, 190, 108859.
- Garcés, M., Cáceres, L., Chiappetta, D., Magnani, N., & Evelson, P. (2021). Current understanding of nanoparticle toxicity mechanisms and interactions with biological systems. *New Journal of Chemistry*, 45(32), 14328–14344.
- García-Sánchez, S., Gala, M., & Žoldák, G. (2021). Nanoimpact in plants: Lessons from the transcriptome. *Plants*, 10(4), 751.
- Ghosh, S. K., & Bera, T. (2021). Molecular mechanism of nano-fertilizer in plant growth and development: A recent account. In *Advances in nano-fertilizers and nano-pesticides in agriculture* (pp. 535–560). Woodhead Publishing.

- Gowtham, H. G., Shilpa, N., Singh, S. B., Aiyaz, M., Abhilash, M. R., Nataraj, K., et al. (2024). Toxicological effects of nanoparticles in plants: Mechanisms involved at morphological, physiological, biochemical and molecular levels. *Plant Physiology and Biochemistry*, 210, 108604.
- Hafeez, A., Razzaq, A., Mahmood, T., & Jhazab, H. M. (2015). Potential of copper nanoparticles to increase growth and yield of wheat. *Journal of Nanoscience Advances in Technology*, 1(1), 6–11.
- Hamers, R. J. (2017). Nanomaterials and global sustainability. *Accounts of Chemical Research*, 50(3), 633–637.
- Harman, G., Khadka, R., Doni, F., & Uphoff, N. (2021). Benefits to plant health and productivity from enhancing plant microbial symbionts. *Frontiers in Plant Science*, 11, 610065.
- Hong, J., Wang, C., Wagner, D. C., Gardea-Torresdey, J. L., He, F., & Rico, C. M. (2021). Foliar application of nanoparticles: Mechanisms of absorption, transfer, and multiple impacts. *Environmental Science: Nano*, 8(5), 1196–1210.
- Hussain, B., Riaz, L., Javeed, K., Umer, M. J., Abbas, Y., Khan, S. W., et al. (2023). Use of nanoparticles and fertilizers in alleviating heavy metals and improving nutrients uptake in plants. In *Sustainable plant nutrition* (pp. 153–178). Academic.
- Ibrahim, E., Xu, L., Nasser, R., Adel, A. S. M., Hafeez, R., Ogunyemi, S. O., et al. (2024). Utilizing zinc oxide nanoparticles as an environmentally safe biosystem to mitigate mycotoxicity and suppress *Fusarium graminearum* colonization in wheat. *Sustainable Materials and Technologies*, 41, e01028.
- Ismailova, G. H., & Azizov, I. V. (2022). Effect of Fe₂O₃ and Al₂O₃ nanoparticles on the antioxidant enzymes in seedlings of *Triticum aestivum* L. *SABRAO Journal of Breeding and Genetics*, 54, 671–677.
- Jasrotia, P., Nagpal, M., Mishra, C. N., Sharma, A. K., Kumar, S., Kamble, U., et al. (2022). Nanomaterials for postharvest management of insect pests: Current state and future perspectives. *Frontiers in Nanotechnology*, 3, 811056.
- Javed, R., Khan, B., Sharafat, U., Bilal, M., Galagedara, L., Abbey, L., & Cheema, M. (2024). Dynamic interplay of metal and metal oxide nanoparticles with plants: Influencing factors, action mechanisms, and assessment of stimulatory and inhibitory effects. *Ecotoxicology and Environmental Safety*, 271, 115992.
- Jiang, Y., Zhou, P., Zhang, P., Adeel, M., Shakoor, N., Li, Y., et al. (2022). Green synthesis of metal-based nanoparticles for sustainable agriculture. *Environmental Pollution*, 309, 119755. [researchgate.net](https://www.researchgate.net)
- Joshi, S., & Joshi, R. (2024). Comparative transcriptome profiling unveils the role of differentially charged gold nanoparticle in growth, metabolic regulation and defence response of micro-propagated *Nardostachys jatamansi* Wall. ex DC. *South African Journal of Botany*, 167, 585–596.
- Kaler, B., Jangir, H., Sarkar, S., Sharma, J., & Das, M. (2024). Nano-pyrite as a plant hormone regulator: Emulating seed hormoprimer. *Modern Agriculture*, 2(1), e23.
- Kapoor, D., Yadav, S., Sharma, M. M. M., & Sharma, P. (2023). Interaction between metal nanoparticles and PGPR on the plant growth and development. In *Nanomaterials and nanocomposites exposures to plants: Response, interaction, phytotoxicity and defense mechanisms* (pp. 327–351). Springer Nature Singapore.
- Kashyap, P. L., Kumar, S., Kaul, N., Aggarwal, S. K., Jasrotia, P., Bhardwaj, A. K., et al. (2022). Nanotechnology for wheat and barley health management: Current scenario and future prospectus. In *New horizons in wheat and barley research: Crop protection and resource management* (pp. 337–363). Springer Nature Singapore.
- Kolesnikov, S., Timoshenko, A., Minnikova, T., Tsepina, N., Kazeev, K., Akimenko, Y., et al. (2021). Impact of metal-based nanoparticles on cambisol microbial functionality, enzyme activity, and plant growth. *Plants*, 10(10), 2080.
- Krumova, E., Benkova, D., Stoyancheva, G., Dishliyska, V., Miteva-Staleva, J., Kostadinova, A., et al. (2024). Exploring the mechanism underlying the antifungal activity of chitosan-based ZnO, CuO, and SiO₂ nanocomposites as nanopesticides against *Fusarium solani* and *Alternaria solani*. *International Journal of Biological Macromolecules*, 268, 131702.

- Kumar, A., Choudhary, A., Kaur, H., Mehta, S., & Husen, A. (2021). Metal-based nanoparticles, sensors, and their multifaceted application in food packaging. *Journal of Nanobiotechnology*, 19(1), 256. [springer.com](https://www.springer.com)
- Li, L., & Kang, Y. T. (2021). Enhancement mechanisms of mass transfer performance by nanoabsorbents during CO₂ absorption process. *International Journal of Heat and Mass Transfer*, 164, 120444.
- Li, Y., Zhang, P., Li, M., Shakoor, N., Adeel, M., Zhou, P., et al. (2023). Application and mechanisms of metal-based nanoparticles in the control of bacterial and fungal crop diseases. *Pest Management Science*, 79(1), 21–36. [researchgate.net](https://www.researchgate.net)
- Lyagin, I., Aslanli, A., Domnin, M., Stepanov, N., Senko, O., Maslova, O., & Efremenko, E. (2023). Metal nanomaterials and hydrolytic enzyme-based formulations for improved antifungal activity. *International Journal of Molecular Sciences*, 24(14), 11359.
- Madkhali, O. A. (2023). A comprehensive review on potential applications of metallic nanoparticles as antifungal therapies to combat human fungal diseases. *Saudi Pharmaceutical Journal*, 31, 101733.
- Malandrakis, A. A., Kavroulakis, N., & Chrysikopoulos, C. V. (2020). Synergy between Cu-NPs and fungicides against *Botrytis cinerea*. *Science of the Total Environment*, 703, 135557.
- Manaf, A., Wang, X., Tariq, F., Jhazab, H. M., Bibi, Y., Sher, A., et al. (2021). Antioxidant enzyme activities correlated with growth parameters of wheat sprayed with silver and gold nanoparticle suspensions. *Agronomy*, 11(8), 1494.
- Marchiol, L., Pilotto, L., Lizzi, D., & Fellet, G. (2022). Spontaneous plant species responses to engineered nanoparticles. In *Plant exposure to engineered nanoparticles* (pp. 83–118). Academic.
- Mares Castro, A., Estrada Monje, A., Saldívar Campos, A. I., & Zaragoza Estrada, A. (2023). Optimization of the antifungal property in a composite of polyurethane and silver nanoparticles against the *Trichophyton rubrum* fungus. *Applied Sciences*, 13(21), 12028.
- Meshksar, M., Makarem, M. A., Hosseini, Z. S., & Rahimpour, M. R. (2022). Effect of nanofluids in solubility enhancement. In *Nanofluids and mass transfer* (pp. 115–132). Elsevier.
- Milewska-Hendel, A., Gepfert, W., Zubko, M., & Kurczyńska, E. (2022). Morphological, histological and ultrastructural changes in *Hordeum vulgare* (L.) roots that have been exposed to negatively charged gold nanoparticles. *Applied Sciences*, 12(7), 3265.
- Mishra, M., Patole, S., & Mohapatra, H. (2021). Nanoparticles: Powerful tool to mitigate antibiotic resistance. In *Sustainable agriculture reviews 49: Mitigation of antimicrobial resistance Vol 2. Natural and synthetic approaches* (pp. 171–204).
- Mouhamad, R. S., Al Khafaji, K. A., Al-Dharob, M. H., & Al-Abodi, E. E. (2022). Antifungal, antibacterial and anti-yeast activities evaluation of oxides of silver, zinc and titanium nanoparticles. *Chemistry International*, 8(4), 159–166.
- Mustafa, H., Ilyas, N., Akhtar, N., Raja, N. I., Zainab, T., Shah, T., et al. (2021). Biosynthesis and characterization of titanium dioxide nanoparticles and its effects along with calcium phosphate on physicochemical attributes of wheat under drought stress. *Ecotoxicology and Environmental Safety*, 223, 112519.
- Natarajan, K., Adhimoolum, K., Vinod, S., Santhanu, K., Natesan, S., Min, T., & Senthil, K. (2024). An investigation on reduction capability of lead and its influence on withanolides in in vitro shoots of *Withania somnifera* (L.) Dunal. *South African Journal of Botany*, 170, 250–259.
- Nazeer, A., Ahmad, F., Verma, N., & Ahmad, S. (2023). Nanomaterials and phytonanobiotechnology. In *Targeted delivery of nanopesticides and nanofertilizers in sustainable agricultural farming* (pp. 51–66). Springer Nature Switzerland.
- Nisar, P., Ali, N., Rahman, L., Ali, M., & Shinwari, Z. K. (2019). Antimicrobial activities of biologically synthesized metal nanoparticles: An insight into the mechanism of action. *JBIC Journal of Biological Inorganic Chemistry*, 24, 929–941.
- Nishino, S., Oiki, S., Yamana, Y., & Hagiwara, D. (2024). Evaluation of antifungal activity of cerium oxide nanoparticles and associated cellular responses. *Bioscience, Biotechnology, and Biochemistry*, 88, zbae101.

- Niu, B., & Zhang, G. (2023). Effects of different nanoparticles on microbes. *Microorganisms*, 11(3), 542.
- Nizamani, M. M., Hughes, A. C., Zhang, H. L., & Wang, Y. (2024). Revolutionizing agriculture with nanotechnology: Innovative approaches in fungal disease management and plant health monitoring. *Science of the Total Environment*, 928, 172473.
- Noori, A., Hasanuzzaman, M., Roychowdhury, R., Sarraf, M., Afzal, S., Das, S., & Rastogi, A. (2024). Silver nanoparticles in plant health: Physiological response to phytotoxicity and oxidative stress. *Plant Physiology and Biochemistry*, 209, 108538.
- Ortiz, A., & Sansinenea, E. (2022). The role of beneficial microorganisms in soil quality and plant health. *Sustainability*, 14(9), 5358. [mdpi.com](https://doi.org/10.3390/s14095358)
- Padilla-Cruz, A. L., Garza-Cervantes, J. A., Vasto-Anzaldo, X. G., García-Rivas, G., León-Buitimea, A., & Morones-Ramírez, J. R. (2021). Synthesis and design of Ag-Fe bimetallic nanoparticles as antimicrobial synergistic combination therapies against clinically relevant pathogens. *Scientific Reports*, 11(1), 5351.
- Parnichkhal, J., & Krishnankutty, R. E. (2022). Chitosan and gold nanoparticles supplementation for augmentation of indole-3-acetic acid production by rhizospheric *Pseudomonas aeruginosa* and plant growth enhancement. *Current Microbiology*, 79(6), 185.
- Parada, J., Tortella, G., Seabra, A. B., Fincheira, P., & Rubilar, O. (2024). Potential antifungal effect of copper oxide nanoparticles combined with fungicides against *Botrytis cinerea* and *Fusarium oxysporum*. *Antibiotics*, 13(3), 215.
- Parveen, S., Wani, A. H., Shah, M. A., Devi, H. S., Bhat, M. Y., & Koka, J. A. (2018). Preparation, characterization and antifungal activity of iron oxide nanoparticles. *Microbial Pathogenesis*, 115, 287–292.
- Patel, A., Patel, N., Ali, A., & Alim, H. (2023). Interaction between metal oxide nanoparticles and PGPR on plant growth and development. In *Nanomaterials for environmental and agricultural sectors* (pp. 221–238). Springer Nature.
- Pathak, A., Haq, S., Meena, N., Dwivedi, P., Kothari, S. L., & Kachhwaha, S. (2023). Multifaceted role of nanomaterials in modulating in vitro seed germination, plant morphogenesis, metabolism and genetic engineering. *Plants*, 12(17), 3126.
- Pattanayak, S. P., Bose, P., & Sunita, P. (2023). Interaction between nanoparticles and phytopathogens. In *Agricultural and environmental nanotechnology: Novel technologies and their ecological impact* (pp. 169–220). Springer Nature.
- Raj, A., Sriwastaw, S., Rai, K. K., Rai, R., Singh, S., & Rai, L. C. (2024). Impact of nanoparticles on biochemical reactions. In *Molecular impacts of nanoparticles on plants and algae* (pp. 249–275). Academic.
- Rajwade, J. M., Oak, M. D., & Paknikar, K. M. (2024). Copper-based nanofungicides: The next generation of novel agrochemicals. In *Nanofungicides* (pp. 141–168). Elsevier.
- Rameez, M., Khan, N., Ahmad, S., & Ahmad, M. M. (2024). Bionanocomposites: A new approach for fungal disease management. *Biocatalysis and Agricultural Biotechnology*, 103115. [researchgate.net](https://doi.org/10.1016/j.bcab.2024.103115)
- Ramezani, M., Asghari, S., Gerami, M., Ramezani, F., & Karimi Abdolmaleki, M. (2020). Effect of silver nanoparticle treatment on the expression of key genes involved in glycosides biosynthetic pathway in *Stevia rebaudiana* B. plant. *Sugar Tech*, 22, 518–527.
- Rawat, M., Yadukrishnan, P., & Kumar, N. (2021). Mechanisms of action of nanoparticles in living systems. In *Research anthology on synthesis, characterization, and applications of nanomaterials* (pp. 1555–1571). IGI Global.
- Roy, I. (2023). Interactions of nanoparticles with plants: Accumulation and effects. In *Bioinspired and green synthesis of nanostructures: A sustainable approach* (pp. 157–188).
- Saeedian Moghadam, E., Bonyasi, F., Bayati, B., Sadeghi Moghadam, M., & Amini, M. (2024). Recent advances in design and development of Diazole and Diazine based fungicides (2014–2023). *Journal of Agricultural and Food Chemistry*, 72(28), 15427–15448.
- Sandhu, Z. A., Raza, M. A., Alqurashi, A., Sajid, S., Ashraf, S., Imtiaz, K., et al. (2024). Advances in the optimization of Fe nanoparticles: Unlocking antifungal properties for biomedical applications. *Pharmaceutics*, 16(5), 645.

- Santás-Miguel, V., Arias-Estévez, M., Rodríguez-Seijo, A., & Arenas-Lago, D. (2023). Use of metal nanoparticles in agriculture. A review on the effects on plant germination. *Environmental Pollution*, 334, 122222.
- Santhoshkumar, R., Parvathy, A. H., & Soniya, E. V. (2024). Biocompatible silver nanoparticles as nanoprimer mediators for improved rice germination and root growth: A transcriptomic perspective. *Plant Physiology and Biochemistry*, 210, 108645.
- Saqib, S., Faryad, S., Afridi, M. I., Arshad, B., Younas, M., Naeem, M., et al. (2022). Bimetallic assembled silver nanoparticles impregnated in *Aspergillus fumigatus* extract damage the bacterial membrane surface and release cellular contents. *Coatings*, 12(10), 1505.
- Sarmast, M. K., Gupta, S. D., & Zhou, J. (2023). Nanoparticles: Phytostimulatory and/or phytotoxic influences. *Frontiers in Plant Science*, 14, 1287686.
- Sembada, A. A., & Lenggoro, I. W. (2024). Transport of nanoparticles into plants and their detection methods. *Nanomaterials (Basel)*, 14(2), 131.
- Shamsabadi, A. A., Sharifian Gh, M., Anasori, B., & Soroush, M. (2018). Antimicrobial mode-of-action of colloidal Ti3C2T x MXene nanosheets. *ACS Sustainable Chemistry & Engineering*, 6(12), 16586–16596.
- Shao, Z., Bian, L., Ahmadi, S. K., Daniel, T. J., Belmonte, M. A., Burns, J. G., et al. (2024). Nuclear pyruvate dehydrogenase complex regulates histone acetylation and transcriptional regulation in the ethylene response. *Science Advances*, 10(30), eado2825.
- Sharma, I., Sharma, M. V., Haque, M. A., & Simal-Gandara, J. (2023). Antifungal action and targeted mechanism of bio fabricated zinc oxide (ZnO) nanoparticles against *Ascochyta fabae*. *Heliyon*, 9(9), e19179.
- Shende, S., Rajput, V. D., Gade, A., Minkina, T., Fedorov, Y., Sushkova, S., et al. (2021). Metal-based green synthesized nanoparticles: Boon for sustainable agriculture and food security. *IEEE Transactions on Nanobioscience*, 21(1), 44–54. [\[HTML\]](#)
- Shi, C., Xiang, L., & Jiahu, G. (2024). Exploring the frontier of fruit diseases management: Advances in nano-based and biocontrol strategies and underlying action mechanism. *South African Journal of Botany*, 166, 612–623.
- Siddiqi, K. S., & Husen, A. (2017). Plant response to engineered metal oxide nanoparticles. *Nanoscale Research Letters*, 12, 1–18.
- Singh, A. D., Sharma, I., Khanna, K., Handa, N., Kumar, P., Ibrahim, M., et al. (2021). Impact of cobalt oxide nanoparticles on the morpho-physiological and biochemical response in plants. In *Plant responses to nanomaterials: Recent interventions, and physiological and biochemical responses* (pp. 249–267) [\[HTML\]](#)
- Soliman, M., Lee, B., Ozcan, A., Rawal, T. B., Young, M., Mendis, H. C., et al. (2022). Engineered zinc oxide-based nanotherapeutics boost systemic antibacterial efficacy against phloem-restricted diseases. *Environmental Science: Nano*, 9(8), 2869–2886.
- Srivastav, A., Shukla, A., Singhal, R. K., Srivastav, S., Ganjewala, D., & Shrivastava, M. (2023). Soil and plant enzymes responses to zinc oxide nanoparticles in submerged rice (*Oryza sativa* L.) ecosystem. *Trends in Sciences*, 20(9), 5558–5558.
- Srivastava, R., Rawat, A. K., Mishra, M. K., & Patel, A. K. (2024). Advancements in nanotechnology for enhanced antifungal drug delivery: A comprehensive review. *Infectious Disorders-Drug Targets (Formerly Current Drug Targets-Infectious Disorders)*, 24(2), 24–36.
- Toffolatti, S. L., Lecchi, B., Maddalena, G., Marciandò, D., Stuknytė, M., Arioli, S., et al. (2024). The management of grapevine downy mildew: From anti-resistance strategies to innovative approaches for fungicide resistance monitoring. *Journal of Plant Diseases and Protection*, 131, 1–8.
- Van Nguyen, D., Nguyen, H. M., Le, N. T., Nguyen, K. H., Nguyen, H. T., Le, H. M., et al. (2022). Copper nanoparticle application enhances plant growth and grain yield in maize under drought stress conditions. *Journal of Plant Growth Regulation*, 41(1), 364–375.
- Verma, B., Yadav, S. K., Yadav, S., Joshi, M. A., Bhowmick, P. K., & Kardam, V. K. (2022). Effect of nanoparticle seed treatment on total dehydrogenase activity and total fungal infection of *Rhizopus* sp., *Aspergillus* sp. and *Penicillium* sp. in paddy seed. *The Pharma Innovation Journal*, 11(1), 1920–1926.

- Wang, X., Xie, H., Wang, P., & Yin, H. (2023). Nanoparticles in plants: Uptake, transport and physiological activity in leaf and root. *Materials*, 16(8), 3097.
- Wojcieszek, J., & Ruzik, L. (2022). Uptake, accumulation, and transformation of metal-based nanoparticles in plants: Interaction of nanoparticles with environmental pollutants. In *Environmental nanopollutants* (pp. 260–284). <https://doi.org/10.1039/9781839166570-00260>
- Wu, H., & Li, Z. (2022). Nano-enabled agriculture: How do nanoparticles cross barriers in plants? *Plant Communications*, 3(6), 100346.
- Wu, X., Tang, T., Wei, Y., Cummins, K. A., Wood, D. K., & Pang, H. B. (2022). Extracellular vesicles mediate the intercellular exchange of nanoparticles. *Advanced Science*, 9(7), 2102441.
- Wu, Y., Wang, Y., Liu, X., & Zhang, C. (2024). Unveiling key mechanisms: Transcriptomic meta-analysis of diverse nanomaterial applications addressing biotic and abiotic stresses in *Arabidopsis thaliana*. *Science of the Total Environment*, 928, 172476.
- Xu, J. L., Luo, Y. X., Yuan, S. H., Li, L. W., & Liu, N. N. (2021). Antifungal nanomaterials: Current progress and future directions. *Innovations in Digital Health, Diagnostics, and Biomarkers*, 1(1), 3–7.
- Yang, X., Alidoust, D., & Wang, C. (2020). Effects of iron oxide nanoparticles on the mineral composition and growth of soybean (*Glycine max* L.) plants. *Acta Physiologiae Plantarum*, 42, 1–11.
- Yin, Y., Miao, J., Shao, W., Liu, X., Zhao, Y., & Ma, Z. (2023). Fungicide resistance: Progress in understanding mechanism, monitoring, and management. *Phytopathology*, 113(4), 707–718.
- Yong, J., Wu, M., Carroll, B. J., Xu, Z. P., & Zhang, R. (2024). Enhancing plant biotechnology by nanoparticle delivery of nucleic acids. *Trends in Genetics*, 40(4), 352–363.
- Yuan, Z., Li, Y., He, Y., Qian, K., & Zhang, Y. (2023). Differential analysis of three copper-based nanomaterials with different morphologies to suppress *Alternaria alternata* and safety evaluation. *International Journal of Molecular Sciences*, 24(11), 9673.
- Zhang, Z., Jin, H., Fang, J., & Fang, S. (2024). Effects of nanoparticle application on *Cyclocarya paliurus* growth: Mechanisms underlying the particle- and dose-dependent response. *Industrial Crops and Products*, 209, 117942.
- Zhao, X., Li, M., & Xu, Z. (2018). Detection of foodborne pathogens by surface enhanced raman spectroscopy. *Frontiers in Microbiology*, 9, 1236.
- Zhu, X., Chen, Y., Yu, D., Fang, W., Liao, W., & Pan, W. (2024). Progress in the application of nanoparticles for the treatment of fungal infections: A review. *Mycology*, 15(1), 1–16.

Chapter 12

Antibacterial Activity of Metal-Based Nanomaterials and Their Morpho-Physiological Responses on Plants



Ashraf Fathy Abd El-Rahman  and Tahany. G. M. Mohammad

Abstract Plant diseases pose a major threat to global food security and environmental sustainability. As climate change worsens, the risks of disease outbreaks and the emergence of new strains of plant pathogens increase. Bacteria are among the most important plant pathogens and have a significant economic impact. Traditional bactericides, such as antibiotics and copper compounds, can cause environmental and health damage and contribute to the emergence of bactericide-resistant bacterial pathogens. Hence, the importance of metal nanoparticles as a promising tool to combat bacterial pathogens, especially bactericide-resistant strains. Metallic nanoparticles exhibit new or improved physical and chemical properties that increase their effectiveness against target organisms and reduce toxicity to non-target organisms. Several nanoparticles (NPs), most notably silver, copper, copper oxide, and zinc oxide NPs, exhibit antibacterial activity against important bacterial plant pathogens. Experiments have shown that nanobactericides can be applied in many agricultural systems and with different application methods to combat bacterial diseases of plants. Given the growing need to use metallic NPs to combat plant diseases, it is important to consider their effects on plants. Despite the evident benefits of using nanomaterials on plants, high doses may cause phytotoxicity. This chapter focuses on the most important metal-based nanomaterials (mNMs) used in combating bacterial plant diseases, their applications, and morpho-physiological responses to plants.

Keywords Plant pathogens · Bacteria · Nanobactericides · Application · Phytotoxicity

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12.1 Introduction

Plant diseases negatively impact biodiversity, crop productivity, and economic conditions in affected areas, causing major threats to global food security and environmental sustainability. The threats are exacerbated by climate change, which may result in increased disease outbreaks, accelerate the development of new pathogenic strains, and threaten agriculture worldwide (Singh et al., 2023a). Bacteria are among the most important plant pathogens, and the economic impact of plant pathogenic bacteria on agriculture is staggering, costing billions of US dollars globally. Traditional pesticides are used to manage plant diseases and can leave potentially harmful residues on plants and the environment. The biggest challenge facing traditional bactericides like antibiotics to manage plant pathogenic bacteria, in addition to their detrimental impact on the environment and human health, is the emergence of multidrug-resistant (MDR) bacterial strains (Islam et al., 2024). Through horizontal gene transfer, genes can be exchanged between bacteria in the plant production environment, such as bacterial plant pathogens, soil bacteria, and bacterial animal pathogens. Resistance to one compound may confer resistance and MDR to other similar, or even different, compounds (Miller et al., 2022). Antimicrobial resistance is a major global issue that has required the search for new strategies to combat microbes. Hence, metal NPs emerge as a promising tool to combat resistant microbes, along with increased efficacy against target organisms and reduced toxicity to non-target organisms (Wahab et al., 2023).

Nanoparticles, small materials ranging in size from 1 to 100 nanometers, have become increasingly popular in recent decades due to their new or improved physical and chemical properties due to their high surface area and nanoscale size compared to bulk materials. These unusual properties have led to innovative applications in many fields, including medicine, pharmacy, agriculture, etc. (Joudeh & Linke, 2022). Numerous applications of nanotechnology are used in agriculture, such as nanopesticides, nanosensors, nanofertilizers, nano-based gene transfer, and the use of nanomaterials to improve soil and enhance plant stress tolerance (Fig. 12.1). Applications of innovative nanotechnology in agriculture are leading to enhanced crop cultivation methods and crop productivity, increased pest control efficiency, improved soil health, etc. (Yadav et al., 2023). Since ancient times, metals have been applied to manage infectious diseases. Due to their broad range of inhibitory effects on bacteria, fungi, and viruses, metal NPs have gained more attention as antimicrobial agents with the advent of nanotechnology (Brandelli et al., 2017). Metal NPs such as Ag, Au, Zn, Fe, Mg, Pd, Cu, Ti, Si, Al, and Se may possess antibacterial properties. Moreover, metal oxide NPs such as Ag₂O, ZnO, CuO, TiO₂, NiO, Fe₃O₄, α -Fe₂O₃, CaO, MgO, Al₂O₃, CeO₂, Mn₃O₄, and ZrO₂ may possess antibacterial properties (Zhang et al., 2022). Nanobactericides can provide an effective alternative against gram-positive and gram-negative bacteria that are resistant to antibiotics and other conventional bactericides (Baker & Perianova, 2019). Metallic NPs act against bacteria through interactions with the cell wall, membrane penetration, generation of reactive oxygen species (ROS), DNA damage, suppression of protein synthesis, and other mechanisms Fig. 12.2.

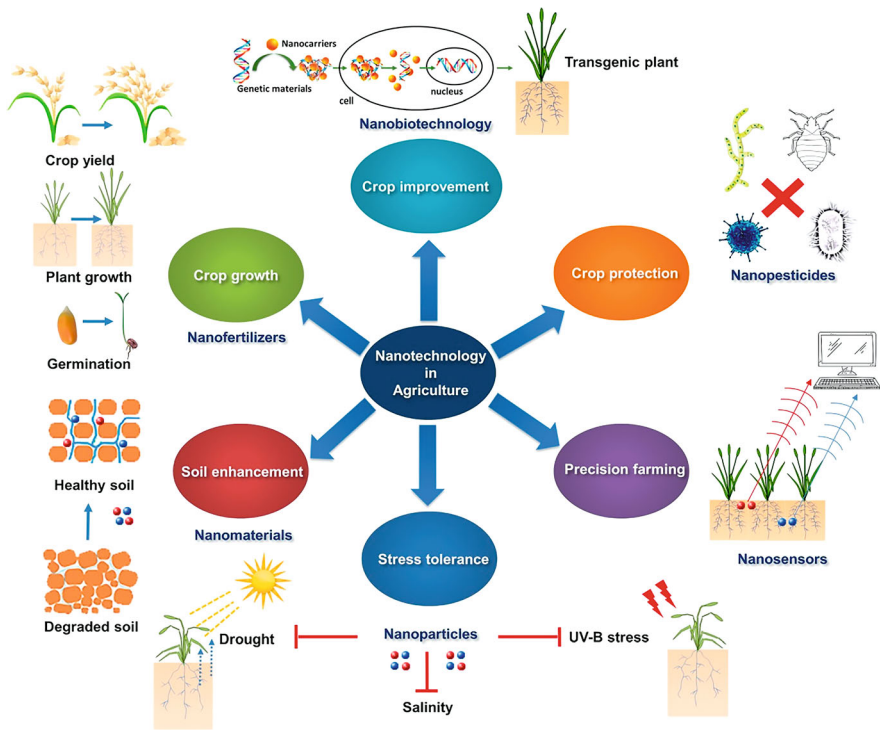


Fig. 12.1 Summary of the most important applications of nanotechnology in agriculture (Shang et al., 2019)

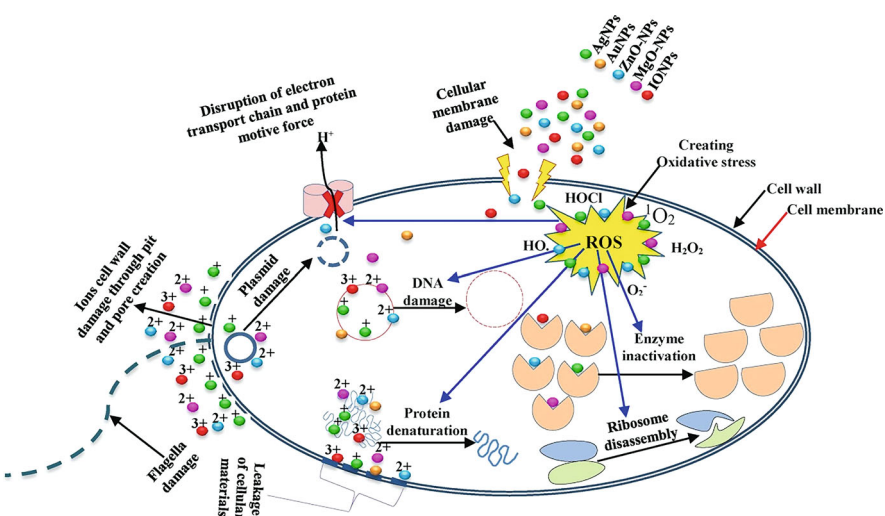


Fig. 12.2 Mechanisms of antibacterial activity of metal-based nanomaterials (Girma, 2023)

12.2 Antibacterial Activity of mNMs Against Phytopathogenic Bacteria and Potential Applications

12.2.1 Silver NPs (AgNPs)

AgNPs represent a promising approach for protection against plant pathogens due to their distinct physicochemical characteristics and attributed antimicrobial properties. AgNPs could provide a strategy to combat bacterial infections in many agricultural systems and growth stages, ultimately improving crop productivity (Kim et al., 2024). The antimicrobial effect of AgNPs is attributed to four distinct mechanisms: adhesion to the membrane surface and cell wall, penetration of AgNPs into the cell causing damage to biomolecules and intracellular structures, AgNP-induced oxidative stress and cytotoxicity due to the generation of reactive oxygen species (ROS) and free radicals, and modulation of signal transduction pathways (Dakal et al., 2016). AgNPs have shown promising antibacterial activity against many plant-pathogenic bacteria, including *Agrobacterium tumefaciens*, *Pectobacterium carotovorum*, *Pseudomonas syringae*, *Ralstonia solanacearum*, *Xanthomonas oryzae*, *Acidovorax citrulli*, and *Enterobacter cloacae* (Table 12.1). AgNPs can be applied to plants and agricultural systems through various methods such as soil applications, plant spraying, and root dipping treatment (Ghazy et al., 2021; Bibi et al., 2023; Orfei et al., 2023; Khan et al., 2024). AgNPs have shown efficacy against strains of MDR plant pathogenic bacteria. AgNPs were found to be naturally protein-coated after biosynthesis using a cell-free filtrate of *Macrophomina phaseolina* and showed an inhibitory effect on the growth of multidrug-resistant *A. tumefaciens* LBA4404-MDR (Chowdhury et al., 2014). One of the issues with the use of AgNPs is their agglomeration, which affects their antibacterial activity (Chen et al., 2023). Modifying the surface of AgNPs with stabilizing agents such as polymers or surfactants prevents agglomeration and enhances stability (Rónavári et al., 2021). The best bactericidal activity against *R. solanacearum* was demonstrated for AgNPs stabilized by Tween 80 after screening a selection of surfactants (Sodium dodecyl sulfate (SDS), Sodium dodecyl benzene sulfonate (SDBS), Octylphenol polyethoxylate (TX-100), and Tween 80) in comparison with pure AgNPs and Ag⁺. In pots, the efficiency of irrigation treatment by AgNPs+Tween 80 (1.22 mg/l) before inoculation with the pathogen on controlling bacterial wilt in tobacco was 96.71%, 90.11%, and 84.21% after 7 days, 14 days, and 21 days, respectively. The disease index was 8.21% at 21 days of treatment compared to the value of 100% in the control (Chen et al., 2016). Treatment of watermelon seeds with AgNPs complexed with bovine submaxillary mucin effectively prevented the transmission of *Acid. citrulli*, the causative agent of bacterial fruit blotch of cucurbits, from seeds to seedlings (Makarovsky et al., 2018). *P. carotovorum* is an extremely damaging phytopathogen that causes soft rot in many plants. Compared with the control treatment, the disease incidence of bacterial rot caused by *P. carotovorum* in sugar beet sprayed with 50, 75, and 100 mg/l AgNPs was reduced by 63.64–94.11% in the greenhouse and field, and sucrose was increased by 11.5–25.7% in sugar beet in the field (Ghazy et al., 2021). AgNPs showed higher

Table 12.1 *In vitro* antibacterial activity of metal-based nanomaterials (mNMs) against plant pathogenic bacteria

Nanomaterial	Source	Size	Concentration	Phytopathogens	Antibacterial effect	References
AgNPs	Synthesis using a cell-free filtrate of <i>Macrophomina phaseolina</i> .	5–40 nm	0.51–5.1 µg/100 µl for IZ test. 2.5 ml (51 µg/ml)/7 ml for GI test.	<i>Agrobacterium tumefaciens</i>	IZs were formed for the normal and multidrug-resistant isolates. Growth kinetics of the bacteria were inhibited.	Chowdhury et al. (2014)
AgNPs	Synthesis using NaBH ₄ + C ₆ H ₅ NaO ₂ . The prepared AgNPs were further stabilized using SDS, SDBS, TX-100, and Tween 80.	10–100 nm	39–0.04 mg/l of AgNPs, 39 mg/l of AgNPs in 0.5% of surfactant to 0.04 mg/l of AgNPs in 9.76 × 10 ⁻⁴ % of surfactant (w/w) for MIC, MBC, and GI tests. 19.5 mg/l of AgNPs and 1.22 mg/l of AgNPs+Tween 80 for TEM, protein damage assay, and FM.	<i>Ralstonia solanacearum</i>	MICs and MBCs were determined. AgNPs+Tween 80 showed stronger bacteriostatic and bactericidal effects. The cell membrane became rough, and the cell structure was distorted (AgNPs, TEM image). Cell structure was looser, and the cytoplasmic density was reduced (AgNPs+Tween 80, TEM image). Structural changes in bacteria and damage to cell membranes were observed (AgNPs+Tween 80, FM image). AgNPs+Tween	Chen et al. (2016)

(continued)

Table 12.1 (continued)

Nanomaterial	Source	Size	Concentration	Phytopathogens	Antibacterial effect	References
AgNPs	Synthesis using bovine submaxillary mucin + $\text{Na}_2\text{B}_4\text{O}_7$.	5–20 nm	0.13–33.5 mg/l for GI test. 0–2.2 mg/l for bactericidal activity test. 10 mg/l for examination by SEM and TEM.	<i>Acidovorax citrulli</i> , <i>Xanthomonas euvesicatoria</i> , and <i>Clavibacter michiganensis</i> subsp. <i>michiganensis</i>	80 caused modifications to cellular proteins and caused damage through AgNPs binding to protein fragments.	Makarovsky et al. (2018)
					Bactericidal effects. <i>Acid. citrulli</i> counts were lowered, and no bacteria could be recovered at 2.2 mg/l. <i>Acid. citrulli</i> cells are irregular in shape, disorganized, and appear damaged with AgNPs on the surface of the cells (SEM and TEM images).	
CuONPs	Synthesis using <i>Carica papaya</i> leaf extracts.	40–80 nm	50, 125, and 250 µg/ml for bacterial growth and viability test, biofilm inhibition assay, and swarming motility test. 250 µg/ml for ATP level measurement. 125 and 250 µg/ml for examination by TEM.	<i>R. solanacearum</i>	The viability of cells decreased. 125 and 250 µg/ml caused a reduction in biofilm at 24 h. A significant decrease in motility. Little ATP production. Damaged in cell structure and absorption of CuONPs by	Chen et al. (2019)

CuNPs, Cu₂ONPs, and CuONPs	Hydrothermally synthesized in the presence of different biocompatible surfactants (Tween 20, TEG, and PEG1000).	46, 39, 12, and 18 nm for CuNPs-Tween20, CuNPs-TEG, Cu ₂ ONPs-Tween20, and CuONPs-PEG1000, respectively.	125 µg/ml for gene expression analysis.	<i>Erwinia amylovora</i> , <i>Xanthomonas campestris</i> , and <i>Pseudomonas syringae</i>	bacteria. Downregulation of pathogenesis and motility genes. IZs were formed. MICs and MBCs were determined.	Gkanatsiou et al. (2019)
CuONPs	Synthesis using streptomycin + gum Arabic + isopropyl alcohol + gamma rays.	20.20 nm	10 µg/ml for IZ and antibiofilm test. 100 µg/ml starting concentration for MIC test.	<i>Dickeya solani</i> , <i>C. michiganensis</i> subsp. <i>sepdonicus</i> , <i>Pectobacterium atrosepticum</i> , <i>R. solanacearum</i> , and <i>Pectobacterium carotovorum</i>	IZs were formed. Biofilm formation was reduced. MICs were determined.	El-Batal et al. (2020)
TiO₂NPs	Synthesis using 2-propanol + deionized water + hydrothermally.	~10–80 nm	9.9 ml (0.5 mg/ml)/100 ml.	<i>E. amylovora</i> , <i>Xanthomonas arboricola</i> pv. <i>juglandis</i> , <i>Pseudomonas syringae</i> pv. <i>tomato</i> , and <i>Allorhizobium vitis</i>	Under UV irradiation, <i>Allor. vitis</i> is more sensitive to TiO ₂ NPs, followed by <i>E. amylovora</i> , <i>Pseu. syringae</i> pv. <i>tomato</i> , and <i>X. arboricola</i> pv. <i>juglandis</i> .	Körösi et al. (2020)

(continued)

Table 12.1 (continued)

Nanomaterial	Source	Size	Concentration	Phytopathogens	Antibacterial effect	References
CuNPs	Synthesis using NaOH +animal protein or non-ionic polymer.	5–10 nm	240 mg/l for the susceptibility test. 75–1200 mg/l of CuNP1 (is 100% CuO and produced through the gradual addition of copper salt solution (Cu (NO ₃) ₂ ·2.5H ₂ O) to animal protein) and 30–240 mg/l of CuNP2 (is a mixture of Cu ₂ O and Cu (OH) ₂ in a ratio of 64% and 36%, respectively, and produced through the rapid addition of non-ionic polymer to copper solution) for the dose-response effect test.	<i>A. tumefaciens</i> , <i>Dickeya dadantii</i> , <i>E. amylovora</i> , <i>P. carotovorum</i> , <i>Pseudomonas domonas corrugata</i> , <i>Pseudomonas savastanoi</i> pv. <i>savastanoi</i> , and <i>Xanthomonas campestris</i> pv. <i>campestris</i>	CuNP1 inhibits only the growth of <i>E. amylovora</i> , while CuNP2 inhibits the growth of <i>E. amylovora</i> , <i>Pseu. savastanoi</i> pv. <i>savastanoi</i> , and <i>X. campestris</i> pv. <i>campestris</i> ; and delayed the growth of <i>A. tumefaciens</i> , <i>P. carotovorum</i> , and <i>D. dadantii</i> . MICs and MBCs of CuNP1 against <i>A. tumefaciens</i> , <i>D. dadantii</i> , <i>E. amylovora</i> , <i>P. carotovorum</i> , and <i>Pseu. savastanoi</i> pv. <i>savastanoi</i> were determined. MIC and MBC of CuNP2 against <i>E. amylovora</i> were determined.	Varympopi et al. (2020)

AgNPs	Synthesis using cell filtrate of <i>Fusarium oxysporum</i> .	16–27 nm	50, 75, and 100 mg/l.	<i>P. carotovorum</i>	IZs were formed.	Chazy et al. (2021)
ZnONPs	Synthesis using <i>Matricaria chamomilla</i> flower extract.	8.9–32.6 nm	6.0, 12.0, and 18.0 µg/ml for IZ test. 18.0 µg/ml for examination by SEM.	<i>R. solanacearum</i>	IZs were formed. Cell deformation, cell wall deterioration, cell membrane disintegration, and leakage of contents (SEM image).	Khan et al. (2021)
AgNPs	Synthesis using <i>Dioscorea bulbifera</i> aerial bulbil extract at room temperature (RT) and 60 °C (H).	ND	50 and 100 mg/l.	<i>Enterobacter cloacae</i>	IZs were formed.	Singh et al. (2021)
FeNPs, CuNPs, CoNPs, and ZnNPs	Synthesis using bacteria.	1–4, 8–14, 9–20, and 4–13 nm, respectively.	100–1000 µg/ml for IZ test. 25–800 µg/ml for MIC and MBC tests.	<i>P. carotovorum</i> , <i>D. solani</i> , <i>Ent. cloacae</i> , <i>P. atrosepticum</i> , <i>R. solanacearum</i> , <i>E. amylovora</i> , and <i>A. tumefaciens</i>	IZs were formed. MICs and MBCs were determined.	Zaki et al. (2021)
AgCINPs	Synthesis using <i>Bacillus mojavensis</i> .	5–35 nm	20, 10, and 5 µg/ml for IZ test and motility assay. 2.5–40 µg/ml for MIC test. 20 µg/ml for examination by SEM and TEM.	<i>R. solanacearum</i>	Radial growth, swarming motility, and swimming motility were inhibited. MIC was determined. Deeply rounded holes form on the surfaces of some cells, resulting in cell deformation (SEM image).	Alamer et al. (2022)

(continued)

Table 12.1 (continued)

Nanomaterial	Source	Size	Concentration	Phytopathogens	Antibacterial effect	References
AgNPs, CuNPs, and AgCuNPs	Synthesis using different methods.	10–170 nm	For IZ test of monometallic NPs: AgNPs = 5 mg/l (AgH ₂ O EID, Ag-H ₂ O gelatin-ERD, Ag-H ₂ O, and AgNH ₄ OH), CuNPs = 1–5 mg/l (Cu-H ₂ O-EID, Cu-H ₂ O gelatin-ERD, Cu-H ₂ O, Cu-H ₂ O-gelatin). 1 mg/l for IZ test to compare AgNPs (prepared in alkaline media with gelatin), CuNPs (prepared in alkaline media with gelatin), and AgCuNPs (prepared in neutral, ammonia, or alkaline media with gelatin).	<i>E. amylovora</i> , <i>Pseu. syringae</i> , and <i>P. carotovorum</i>	Damage of cell walls and cytoplasmic membrane and cell deformation (TEM image). IZs were formed. <i>E. amylovora</i> rod-shaped cells were crushed into cocci shapes or became shapeless, and <i>Pseu. syringae</i> cells lost their normal form and became an amorphous mass (LM image) around the lysis zones formed by AgCuNPs prepared in alkaline media with gelatin.	Doolotkeldieva et al. (2022)

ZnONPs	Synthesis using extracts of <i>Garcinia mangostana</i> peels + NaOH (ZnONPs-Gm) and <i>Eichhornia crassipes</i> + NaOH (ZnONPs-Ec).	154.41 × 172.89 nm and 142.16 × 160.30 nm, respectively.	2–10 mg/ml	<i>Xanthomonas oryzae</i> pv. <i>oryzae</i> , <i>R. solanacearum</i> , and <i>Xanthomonas axonopodis</i> pv. <i>citri</i>	IC ₅₀ s were determined.	Jaiithon et al. (2022)
CuNPs	Synthesis using <i>Shewanella</i> sp.	30–190 nm	10–500 mg/l for IZ test. 10–200 for GI test. 100 mg/l for examination by SEM and TEM.	<i>R. solanacearum</i> and <i>X. axonopodis</i>	Above 25 mg/l, <i>R. solanacearum</i> showed IZs, and no IZs for <i>X. axonopodis</i> . The bacterial biomass of <i>R. solanacearum</i> was reduced at concentrations of 50, 100, and 200 mg/l. <i>R. solanacearum</i> cells show cell wall distortion, which was not observed in <i>X. axonopodis</i> (SEM image). Particles were not deposited inside the <i>R. solanacearum</i> cells but were peeled off the cell membranes (TEM image).	Luong et al. (2022)

(continued)

Table 12.1 (continued)

Nanomaterial	Source	Size	Concentration	Phytopathogens	Antibacterial effect	References
CuNPs	Varympopi et al. (2020)	5–10 nm	18.75–150 mg/l of CuNP1 and 30–240 mg/l of CuNP2 for MIC and MBC tests.	<i>Xanthomonas campestris</i> pv. <i>vesicatoria</i>	MIC, MIC50, MIC90, and MBC were determined.	Varympopi et al. (2022)
AgNPs	Synthesis using aqueous extract of <i>Hedera nepalensis</i> .	<50 nm	15.62–1000 µg/ml of extract-free AgNPs (Ef-AgNPs) and extract-mixed AgNPs (Em-AgNPs) for GI test. 62.5, 250, and 1000 µg/ml of Ef-AgNPs and Em-AgNPs for IZ test.	<i>P. carotovorum</i> , <i>P. atrosepticum</i> , and <i>R. solanacearum</i>	Bacterial growth was inhibited. IZs were formed.	Bibi et al. (2023)
AgNPs	Synthesis using an aqueous plant extracts of <i>Salvia nubicola</i> .	23–63 nm	78.1–500 µg/ml extract-free AgNPs and AgNPs with plant extracts.	<i>R. solanacearum</i>	Bacterial growth was inhibited.	Dilbar et al. (2023)
ZnONPs	Synthesis using starch.	340–720 nm, with some around 100 nm	0.125, 0.25, 0.5, and 1 mg/ml for cell viability, growth curve, and efflux of cytoplasm tests. 0.50 mg/ml for the live/dead experiment. 0.125, 0.25, 0.50 for motility test. 0.125 mg/ml for bio-film assay and	<i>Pseudomonas syringae</i> pv. <i>tabaci</i>	Cell viability: complete growth inhibition at 0.5 mg/ml. Growth curve: 0.5 mg/ml completely kills the bacteria. Efflux of cytoplasm test: cell contents leakage. Live/dead	Fan et al. (2023)

				molecular responses of bacteria. 0.25 mg/ml for examination by SEM and TEM.			experiment: bacteria completely killed. The swimming and twitching motility were greatly reduced. The biofilm formation decreased dramatically. Suppression of the expression of several bacteria genes. The cell envelopes were disrupted and shrunken (SEM image). ZnONPs penetrated cell envelopes (TEM image).	
CuONPs	Synthesis using leaf extract of <i>Spirodella polyrhiza</i> .	~100 nm	100 µg/ml			<i>P. carotovorum</i>	IZ was formed.	Khan et al. (2023a)
AgNPs	Electrochemically synthesized silver ultra nanoclusters (ARGIR-IUM-SUNCs).	1.79 nm	Antimicrobial activity test: 0.1–1.0 mg/l for <i>Pseu. syringae</i> pv. <i>tomato</i> and <i>Xanthomonas vesicatoria</i> ; 0–6 mg/l for <i>C. michiganensis</i> subsp. <i>michiganensis</i> ; and 0.023, 0.23, and 2.3 mg/l for <i>Xylella fastidiosa</i> subsp.			<i>Pseu. syringae</i> pv. <i>tomato</i> , <i>X. vesicatoria</i> , <i>C. michiganensis</i> subsp. <i>michiganensis</i> , and <i>Xyl. fastidiosa</i> subsp. <i>pauca</i> strain De Donno	EC ₅₀ s were determined. Biofilm formation was decreased.	Orfei et al. (2023)

(continued)

Table 12.1 (continued)

Nanomaterial	Source	Size	Concentration	Phytopathogens	Antibacterial effect	References
CuONPs and MgONPs	Synthesis using polyvinylpyrrolidone + NaOH, and NaOH, respectively.	3.59–6.05 and 3.71–6.58 nm, respectively.	<i>pauca</i> strain De Donno. Biofilm formation test: 0.023, 0.23, and 2.3 mg/l for <i>Xyl. fastidiosa</i> subsp. <i>pauca</i> strain De Donno and 0.1–1.0 mg/l for the others.	<i>R. solanacearum</i>	IZs were formed. MICs and MBCs were determined. Decreased levels of total lipids and neutral lipids accompanied by increased levels of phospholipids. Nanoparticles adhere to the surface of cells and penetrate inside them, causing major structural changes and damage (TEM image).	Rabea et al. (2023)
AgNPs	Synthesis using tree leaf extract of <i>Azadirachta indica</i> (A-AgNPs) and <i>Mangifera indica</i> (M-AgNPs).	11.45 and 22 nm, respectively.	6, 8, and 10 µl/ml.	<i>Xanthomonas Oryzae</i>	IZs were formed.	(Rana et al., 2023)

FeNPs, CuNPs, CoNPs, and ZnNPs	Synthesis using bacteria.	Zaki et al. (2021)	300 µg/ml	<i>P. carotovorum</i> , <i>D. solani</i> , <i>Ent. cloacae</i>	DNA, protein, and carbohydrate degradation. Cell collapse and holes appear in the cell wall (SEM images). NPs penetration into the cell, condensation of the cytoplasm, and the appearance of vacuoles and gaps (TEM image).	Shoeb et al. (2023)
CuONPs	Synthesis using <i>Serratia</i> sp.	20–40 nm	50 µg/ml	<i>Xanthomonas</i> sp.	IZ was formed.	Singh et al. (2023b)
AgNPs and ZnONPs	Synthesis using fungal extract of <i>Fusarium solani</i> .	2.99–21.53, 54.44–209.69, and 64.84–443.02 nm for AgNPs, ZnONPs (1), and ZnONPs (2), respectively.	1–2048 µg/ml for AgNPs synthesized by fungal extract + 1 mM AgNO ₃ , ZnONPs (1) synthesized by a combination of fungal extract + ZnSO ₄ + NaOH in a ratio of 1:1:1 (v/v), and ZnONPs (2) synthesized by fungal extract + ZnSO ₄ (1:1, v/v).	<i>A. tumefaciens</i> , <i>P. carotovorum</i> , <i>Pseud. syringae</i> , and <i>X. campestris</i>	MICs and MBCs were determined.	Trzcińska-Wencel et al. (2023)
CuNPs and AgNPs	Synthesis using gum arabic + C ₆ H ₈ O ₆ + NaOH, and rice leaf extract, respectively.	<100 nm	250 mg/l CuNPs, 500 mg/l CuNPs, 500 mg/l CuNPs + 50 mg/l AgNPs, and 250 mg/l CuNPs + 25 mg/l AgNPs.	<i>X. oryzae</i> pv. <i>oryzae</i>	IZs were formed.	Chowdhury et al. (2024)

(continued)

Table 12.1 (continued)

Nanomaterial	Source	Size	Concentration	Phytopathogens	Antibacterial effect	References
AgNPs	Synthesis using leaf extract of <i>Rubus fruticosus</i> .	50–120 nm	1.9–1000 µg/ml for IG test for AgNPs alone and AgNPs embedded in plant extract (AgNPs + PE).	<i>R. solanacearum</i> and <i>P. atrosepticum</i>	Bacterial growth was inhibited.	Khan et al. (2024)
ZnONPs	Synthesis using <i>Citrus limetta</i> peel extract.	16.58 nm	100, 250, and 500 µg/ml.	<i>P. carotovorum</i> , <i>R. solanacearum</i> , and <i>C. michiganensis</i>	IZs were formed.	Rashid et al. (2024)
CuNPs and AgNPs	Synthesis using <i>Citrus sinensis</i> fruit peel extract.	400–500 nm	0.25, 0.50, and 1.0 g/20 ml.	<i>P. carotovorum</i>	IZs were formed.	Usman et al. (2024)

IZ inhibition zone, GI growth inhibition, MIC minimal inhibitory concentration, MBC minimum bactericidal concentration, EC₅₀ half maximal effective concentration, IC₅₀ half-maximal inhibitory concentration, SDS sodium dodecyl sulphate, SDBS sodium dodecyl benzene sulfonate, TX-100 octylphenol polyethoxylate, TEG tetraethylene glycol, PEG1000 tetraethylene glycol, Tween 20 polysorbate 20, Tween 80 polysorbate 80, ND not determined, SEM scanning electron microscope, TEM transmission electron microscopy, FM fluorescence microscopy, LM light microscope

efficiency than CuNPs in protecting potato slices from soft rot caused by *P. carotovorum* (Usman et al., 2024). The antibacterial activity of AgNPs can be affected by the synthesis temperature. The synthesis temperature can regulate the size and shape of NPs (Smiechowicz et al., 2021). Biosynthesized AgNPs using 20% (v/v) *Dioscorea bulbifera* L. aerial bulbil extract at 60 °C showed more effective growth inhibition than biosynthesized at room temperature against the plant pathogen *Ent. cloacae* (Singh et al., 2021). The type of plant extract used to synthesize AgNPs may also affect their antibacterial activity. AgNPs synthesized using *Azadirachta indica* have been shown to inhibit the growth of *X. oryzae*, the causative agent of rice leaf blight disease, compared to AgNPs synthesized using *Mangifera indica* (Rana et al., 2023). One promising technique to reduce the toxicity and increase the efficacy of AgNPs is the bioconjugation of AgNPs with plant extracts, which alters the properties of the NPs. The natural molecules in the plant extracts reduce the toxicity of AgNPs while enhancing their antibacterial efficacy (Majeed et al., 2022). In *in vitro* antibacterial experiments, extract-mixed AgNPs (Em-AgNPs) outperformed extract-free AgNPs (Ef-AgNPs) in inhibiting *P. carotovorum* and *R. solanacearum*, indicating a potential synergistic effect for plant extract and AgNPs. Soft rot symptoms of *P. carotovorum* did not develop in potato tubers treated with Em-AgNPs at a dose of 62.5 µg/ml, while the control treatment was completely infected by the bacteria. Soil-drenching with Em-AgNPs (125 µg/ml) prevented wilt symptoms of *R. solanacearum* in tomato plants with no noticeable phytotoxicity, but symptoms of infection developed in the control treatment (Bibi et al., 2023). Similar results were observed when AgNPs were combined with *Salvia nubicola* aqueous extract, which exhibited greater antibacterial activity against *R. solanacearum* than when the plant extract and AgNPs were used separately (Dilbar et al., 2023). In contrast, AgNPs alone inhibited the growth of *R. solanacearum* and *Pectobacterium atrosepticum* more than AgNPs embedded in the plant extract of *Rubus fruticosus* (AgNPs + RPE) *in vitro*. At the same time, the control plants demonstrated severe symptoms in pots and died, while the potato plants that were treated (soil drench) with 250 µg/ml of AgNPs and AgNPs + RPE after 3 days of being inoculated with *P. atrosepticum* showed no symptoms; the plants were vigorous, and there was no visible phytotoxicity (Khan et al., 2024). The application method can influence the effectiveness of AgNPs in controlling plant bacterial diseases. In the growth chamber experiment, spraying tomato leaves with electrochemically synthesized AgNPs (ARGIR-IUM-SUNCs) could not protect tomato plants against *Pseu. syringae* pv. *tomato*; however, root dipping application significantly protected against the disease at 10 mg/l with no toxic effects (Orfei et al., 2023).

12.2.2 Copper-Based NPs (Cu-Based NPs)

Copper has been used as an antimicrobial since ancient times. The main mechanism of action of copper against bacteria is the generation of ROS, which causes irreversible damage to the cell membrane (Salah et al., 2021). Copper is an essential nutrient

for humans, animals, and plants since it is a component of numerous important proteins. Its deficit or excess can be detrimental to human health and the environment. For example, studies have found that an increased incidence of Alzheimer's disease in humans is associated with a breakdown in copper homeostasis regulation (Coelho et al., 2020). Furthermore, high copper concentrations in soil, for example, cause severe loss of function and selective pressure on microbial communities (Shaw et al., 2020). Nanopesticides, including Cu-based NPs, have promising potential due to their low application doses and increased efficacy, contributing to a potential reduction in environmental damage (Vignardi et al., 2020). Cu-based NPs have an antibacterial effect by generating ROS, rupturing cell walls and membranes, and reacting with proteins and DNA (Ma et al., 2022). Cu-based NPs have shown good antibacterial activity against many plant-pathogenic bacteria, including *Erwinia amylovora*, *Xanthomonas campestris*, *Pseu. syringae*, *Dickeya solani*, *Clavibacter michiganensis* subsp. *sepdonicus*, *R. solanacearum*, *Pseudomonas savastanoi* pv. *savastanoi* (Table 12.1). The preparation of copper nanoparticles (CuNPs) is more difficult than preparing NPs of other metals. It is considered a challenge as these CuNPs are subject to rapid oxidation to Cu^{2+} ions in air or in aqueous media, leading to the agglomeration of particles. Protective polymers or surfactants can be used to inhibit oxidation and avoid this problem (Bhagat et al., 2021; Gkanatsiou et al., 2019). Cu-based NPs synthesized in the presence of different surfactants, polyethylene glycol (PEG1000), tetraethylene glycol (TEG), and polysorbate 20 (Tween 20), were tested against three phytopathogenic bacteria. CuNPs-Tween 20 and CuNPs-TEG showed the highest inhibition zones compared to Cu_2ONPs -Tween 20 and CuONPs -PEG1000 against *E. amylovora*, *X. campestris*, and *Pseu. syringae*. CuNPs-Tween 20 showed antimicrobial activity against *Pseu. syringae* at all tested concentrations (200, 150, and 100 $\mu\text{g/ml}$) when spraying *Phaseolus vulgaris* in pots. When Cu_2ONPs -Tween20 (250, 200, and 150 $\mu\text{g/ml}$) were used, bacterial growth was inhibited by just one to two orders of magnitude, which was similar to Kocide 2000 35WG (1000 $\mu\text{g/ml}$). Cu-based NPs did not reduce chlorophyll content, and there was no difference in quantum yield or CO_2 assimilation measurements when compared to the water control, but Kocide 2000 35 WG treatment had a detrimental impact on chlorophyll content. Furthermore, plants treated with CuNPs-Tween 20 at a concentration of 150 $\mu\text{g/ml}$ showed a substantial increase in plant height compared to the water control and Kocide 2000 35 WG treatment (Gkanatsiou et al., 2019). In pots, when compared to the control treatment, it was found that CuNP1 (produced through the gradual addition of copper salt solution to animal protein) and CuNP2 (produced through the rapid addition of non-ionic polymer to copper solution) at a concentration of 300 mg/l significantly decreased the total population of *X. campestris* pv. *vesicatoria* in tomato leaves until 4 days post inoculation (dpi). However, at 7 and 11 dpi, the respective drop in internal population density was not statistically significant. The available total copper concentration on the surface of tomato leaves was 4.25, 40.8, and 90 mg/l in water treatment, CuNP1, and CuNP2, respectively (Varympopi et al., 2022). Brown rot (bacterial wilt) is one of the most important bacterial diseases that cause

significant economic losses in potatoes, and control methods are limited and often ineffective (Tessema & Seid, 2023). Bacterial wilt was successfully reduced in tobacco seedlings treated with CuONPs via root irrigation 48 h after *R. solanacearum* inoculation. After a 20-day incubation period in a greenhouse, the disease index in plants treated with deionized water was 97.3%, while plants treated with CuONPs at doses of 50, 125, and 250 µg/ml showed disease indexes of 74.2, 62.2, and 38.1%, respectively (Chen et al., 2019).

12.2.3 Zinc Oxide NPs (ZnONPs)

Zinc oxide is an agricultural input used, for example, as a fertilizer. ZnO has an antimicrobial effect against bacteria and fungi by generating ROS and by direct contact with cell walls. In addition, the partial solubility of zinc oxide (ZnO) in water provides Zn^{2+} ions, which contribute to the antimicrobial effect of ZnO (Pasquet et al., 2014). ZnONPs have appealing antibacterial capabilities due to the increased specific surface area, as smaller particle size leads to higher particle surface reactivity (Sirelkhatim et al., 2015). ZnONPs have shown antibacterial activity against several plant pathogenic bacteria, including *P. carotovorum*, *R. solanacearum*, *C. michiganensis*, *Xanthomonas axonopodis* pv. *citri*, *Pseu. syringae* pv. *tabaci*, and *Xanthomonas oryzae* pv. *oryzae* (Table 12.1). *Pseu. syringae*, a Gram-negative bacterium, causes significant losses by infecting many host plants. Historically, copper compounds have been used to treat agricultural diseases, but the emergence of copper-resistant bacteria is a concern (Córdova et al., 2023). In pot experiments, the spray of tobacco plants with ZnONPs (0.25 mg/ml) efficiently controlled tobacco wildfire disease caused by *Pseu. syringae* pv. *tabaci* with a disease spot diameter of 0.75 cm compared to 4.06 cm in water-treated plants. ZnONPs (0.5 mg/ml) have been shown to enhance tobacco resistance and have no apparent toxicity to tobacco (Fan et al., 2023). ZnONPs (0.1 mg/ml) foliar spray on lentil (*Lens culinaris*) plants in pots increased plant growth and reduced the severity of diseases caused by *Xanthomonas axonopodis* pv. *phaseoli* and *Pseu. syringae* pv. *syringae* (Siddiqui et al., 2018). Potatoes are affected by many important bacterial diseases, both in the field and during storage. Bacterial diseases are considered one of the most important biological obstacles to potato production, and most of these diseases have no effective control methods (Czajkowski et al., 2011). After 48 h of incubation at 30 °C, potato slices treated with ZnONPs (100 and 1000 µg/ml) and inoculated with *P. carotovorum*, *R. solanacearum*, and *C. michiganensis* showed no signs of infection, compared to a diameter infection area of 17.26, 21.82, and 20.71 mm, respectively, in the control group (Rashid et al., 2024). Compared to the untreated control, adding 4 and 8% ZnONPs to soil inoculated with *R. solanacearum* increased the growth of tomato plants in pots and decreased soil bacterial population and disease severity (Khan et al., 2021).

12.2.4 Others

Other forms of mNMs have shown antibacterial activity against plant pathogenic bacteria (Table 12.1). FeNPs had the highest antibacterial activity when tested against *P. carotovorum*, *Ent. cloacae*, *P. atrosepticum*, *D. solani*, *R. solanacearum*, *E. amylovora*, and *A. tumefaciens*, followed by CuNPs, CoNPs, and ZnNPs (Zaki et al., 2021). After 48 h of incubation at 28 °C, the potato tuber treated with FeNPs, CuNPs, and CoNPs (300 µg/ml) and inoculated with *P. carotovorum*, *D. solani*, and *Ent. cloacae* did not exhibit any indications of rot; the control treatments revealed soft rot areas. Pot experiments showed that potato plants treated with FeNPs (300 µg/ml) after infection with *D. solani* showed a significant increase in fresh and dry weight compared to those treated with copper pesticide and healthy plants. These results supported using FeNPs as an alternative to copper pesticides in controlling potato soft rot and blackleg diseases (Shoeib et al., 2023). Biogenic AgCINPs exhibited good antibacterial activity against *R. solanacearum* at 20 µg/ml. AgCINPs greatly reduced the swimming and swarming motility of *R. solanacearum* (Alamer et al., 2022). Pots experiment showed that CuONPs (0.5 mg/ml) and MgONPs (0.6 mg/ml) reduced potato brown rot caused by *R. solanacearum* by 71.2% and 69.4%, respectively, compared with the control treatment (Rabea et al., 2023). Antibacterial activities of monometallic Ag and Cu NPs (MNPs) and bimetallic AgCu NPs (BNPs) were studied against *E. amylovora*, *Pseu. syringae*, and *P. carotovorum*. The AgCuNPs at 1 mg/l had high antibacterial activity against the tested bacteria with inhibition zones of 6–8 mm compared to inhibition zones of 2–5 and 4–4.7 mm for AgNPs and CuNPs, respectively (Doolotkeldieva et al., 2022). The photocatalytic activity of TiO₂NPs and the ability to photodegrade phenol were examined, and it was also used to inactivate some important plant pathogenic bacteria. Under UV irradiation, TiO₂NPs showed antimicrobial activity, and the kinetic curves showed that *Allorhizobium vitis* was the most sensitive bacteria, followed by *E. amylovora*, *Pseu. syringae* pv. *tomato*, and *Xanthomonas arboricola* pv. *juglandis* (Kőrösi et al., 2020).

12.3 Morpho-Physiological Responses of Plants to mNMs

NPs have physiological and morphological effects on plants, which can be negative or positive (Goswami et al., 2019). NPs can positively or negatively affect seed germination, plant growth, chlorophyll synthesis, plant hormone balance, plant enzyme activity, plant productivity, etc. (Table 12.2). Particle properties including size, shape, aggregation state, surface coating, concentration, exposure time, and type of NPs influence how NPs affect plants. Moreover, plant responses to NPs are strongly influenced by their species, age, and growth stage (Xalxo et al., 2021). Research has shown that different concentrations of NPs have different effects on seed germination, plant growth, and other physiological and morphological

Table 12.2 Morpho-physiological effect of metal nanoparticles on some plant species

Nanoparticles	Size	Concentration	Plant species	Application method	Effect	References
ZnONPs	12–24 nm	1000 and 2000 mg/l	Habanero pepper (<i>Capsicum chinense</i>)	Foliar treatment	Fruit yield, biomass accumulation, plant height, stem diameter, and chlorophyll content all increased at 1000 mg/l. At 2000 mg/l, plant growth was negatively affected, but fruit quality increased.	García-López et al. (2019)
AgNPs	ND	20–60 mg/l	Fenugreek (<i>Trigonella foenum-graecum</i>)	Foliar treatment	Improved the growth parameters, increased photosynthetic pigment and indole acetic acid (IAA), increased yield quantity and quality, and increased the antioxidant activity of the harvested seeds.	Sadak (2019)
FeNPs, ZnNPs, and CuNPs	27.0, 54.0, and 79.0 nm, respectively.	10.0, 3.0, and 0.6 mg/l for FeNPs. 3.0, 1.0, and 0.2 mg/l for ZnNPs. 0.04, 0.004, and 0.0008 mg/l for CuNPs.	tomato (<i>Lycopersicon esculentum</i>)	Plant cultivation on MS medium containing NPs and their combinations instead of salts.	Increased seed germination, root length, and root activity.	Chen et al. (2020)
AgNPs	45 nm	10, 20, and 30 mg/l	tomato (<i>L. esculentum</i>)	Plants were grown in Hoagland media containing NPs.	Affects plant growth, water and nutrient dynamics, vascular tissue structure, and the electrochemical potential of plant cells.	Noori et al. (2020)
CuONPs	~ 6.6 nm	0.2–300 µg/ml		Seed treatment	The low concentrations, up to 40 µg/ml, enhanced	Pelegriño et al. (2020)

(continued)

Table 12.2 (continued)

Nanoparticles	Size	Concentration	Plant species	Application method	Effect	References
AgNPs			lettuce (<i>Lactuca sativa</i>)		the seed germination. Concentrations higher than 40 µg/mL inhibit seed germination.	
	6–24 nm	10–50 mg/l	<i>Maerua oblongifolia</i>	Nodal segments of the plant were transplanted into MS media containing NPs.	The number, length, fresh weight, dry weight, and chlorophyll content of the shoots were all increased at 20 mg/l. At 10 mg/l, the maximum amount of total protein was determined. Proline and the enzymes catalase and superoxide dismutase were increased at 40 and 50 mg/l.	Shaikhaldin et al. (2020)
CuONPs	<50 nm	62.5, 125, and 250 mg/l	Rice (<i>Oryza sativa</i>)	Seedlings exposed to nanoparticles under hydroponic conditions.	Caused oxidative stress and reduced rice seedling growth and chlorophyll content.	Yang et al. (2020)
ZnONPs	15–40 nm	50–200 mg/l	Wheat (<i>Triticum aestivum</i>) and maize (<i>Zea mays</i>)	Seed treatment and plant growth in 1/4th strength Hoagland's solution containing NPs.	Declines in dehydrogenase and increases in alpha-amylase, biomass, length, photosynthetic pigments, and malondialdehyde content. Antioxidant enzymes increase up to 100 mg/l of NPs but decrease at 150–200 mg/l.	Srivastav et al. (2021)
AgNPs	35 nm	10–1000 µM	<i>Sorghum bicolor</i>	Seed treatment	Germination was disrupted after treatment	Ziotti et al. (2021)

					with AgNP and AgNO ₃ . AgNPs are less toxic than the AgNO ₃ matrix. AgNPs promoted more effective protective mechanisms than AgNO ₃ .	
AgNPs and FeNPs	81.84 and 207.30 (hydrodynamic diameter), respectively.	1.53×10^{13} NPs/m ² and 2.35×10^{11} NPs/m ² , respectively.	Soybean (<i>Glycine max</i>)	Soil treatment	AgNPs reduce root dry weight, cause oxidative stress in the root, and decrease stomatal conductance. FeNPs increase the levels of oxygen peroxide and cause root lignification (a defense mechanism).	Guilger-Casagrande et al. (2022)
ZnONPs	84.5 nm (hydrodynamic diameter)	20–200 mg/l	Mustard (<i>B. juncea</i>)	Soil treatment	Increased the growth, chlorophyll, shoot biomass, and net photosynthesis. Increased K, Fe, Zn, flavonoid content, and antioxidant capacity.	Geremew et al. (2023)
AgNPs, AuNPs, CeO₂NPs, Fe₂O₃NPs, SiO₂NPs, SnO₂NPs, and TiO₂NPs	10, 20, 4, 6, 10, 6, and 6 nm, respectively.	0.004 (40 mg/l), 0.002 (20 mg/l), 3, 3, 6, 3, and 6%, respectively.	Oakleaf lettuce (<i>L. sativa</i> var. <i>foliosa</i>)	Foliar treatment	Initially, chlorosis, necrosis, and leaf vein deformation occurred, and then the plant recovered. Change in reflectance indices and chlorophyll fluorescence parameters depending on NPs type.	Kalisz et al. (2023)
ZnONPs	18.730–25.531 nm	10, 20, and 40 mg/l	<i>Echinops macrochaetus</i>	Irrigation treatment	At 10 mg/l, there was an increase in biomass,	Khan et al. (2023b)

(continued)

Table 12.2 (continued)

Nanoparticles	Size	Concentration	Plant species	Application method	Effect	References
AgNPs, CuNPs, and CuAgNPs	25–86 nm	1–20 mg/l (seed treatment) and 20–100 mg/l (foliar treatment)	Pepper (<i>Cap-sicum annuum</i>)	Seed and foliar treatment	chlorophyll, and caroten-oid. At 20 and 40 mg/l, antioxidant enzymes, total crude and soluble protein, proline, and thiobarbituric acid reac-tive substances increased. Enhanced seed germina-tion and plant growth. Chlorophyll, carotenoids, total phenolic content, and total flavonoid con-tent increased.	Mawale et al. (2024)
ZnONPs	71.13 nm (hydro-dynamic diameter)	250–500 mg/l	wheat (<i>Triticum aestivum</i>)	Seed treatment	Shoot length, root length, and the fresh and dry weights of the leaf and root tissues increased at 250 mg/l. These param-eters decrease at 500 mg/l. ZnONPs enhance total chlorophyll, malondialdehyde, total protein, proline, and glycine-betaine. More-over, there is an increase in the activity of antioxi-dant enzymes.	Pandya et al. (2024)
AgNPs	20 nm	80–100 mg/l	<i>Lepidium sativum</i>	Irrigation treatment	Induce oxidative, reduce plant growth, and reduce pigment content in leaves.	Shahraki et al. (2024)

characteristics of plants. At low concentrations, some NPs can improve germination, promote plant growth, etc., but the opposite can happen at high concentrations (Pandya et al., 2024; Pelegrino et al., 2020). NPs positively improve seed germination by overcoming seed dormancy, improving nutrient utilization and water uptake, and increasing the activity of some enzymes. Conversely, NPs may negatively affect seed germination by disrupting hormonal balance, inducing seed dormancy, and stress events (Ahmad et al., 2022). Plant growth parameters such as plant height, root length, leaf number, fruit size and yield, seed germination, fresh shoots, and root biomass are improved by low doses of NPs (Nafees et al., 2020). Excessive doses of NPs may inhibit plant growth and development. Excessive concentrations of NPs may damage the structure of chloroplasts, decrease the number of grana and thylakoids, and lower the amount of chlorophyll; low concentrations may improve the production of plant photosynthetic pigments and proteins (Li et al., 2024). Despite the abundance of research on the morphological, physiological, biochemical, and molecular responses of plants upon exposure to NPs, studies investigating the interactions between NPs and plant hormones and their effects on plant growth are still limited (Kandhol et al., 2022). Exposure to NPs causes changes in the transcription of genes involved in plant hormone biosynthesis or signal transduction, such as those involved in auxin repression or auxin response, abscisic acid production, or ethylene signaling components (Tripathi et al., 2022). Nanoparticles can enhance the activity of antioxidant enzymes including catalase (CAT), peroxidase (POD), and superoxide dismutase (SOD) in plants, allowing them to withstand environmental challenges; however, excessive or inappropriate use of nanoparticles can produce oxidative stress, which reduces plant growth and development (Li et al., 2024).

12.4 Toxicity of mNMs on Plants

Despite the obvious beneficial aspects of NPs on plants, overdoses of them can cause phytotoxicity, leading to negative effects. In numerous plant species, NPs cause cell death by stimulating cytotoxic and genotoxic effects, as well as generating ROS (Thiruvengadam et al., 2024). Reducing seed germination and biomass production, disrupting photosynthesis, inducing oxidative stress, affecting cell membrane integrity, changing gene expression, damaging DNA, and genetic variations in plants are among the most prominent expected effects of nanoparticle toxicity on plants (Gowtham et al., 2024). One of the most prominent mechanisms contributing to nanomaterial phytotoxicity is ROS production, which causes oxidative stress (Table 12.3). Oxidative stress is a shift in the balance between prooxidative and antioxidative reactions and results from the excessive production and accumulation of ROS such as $O_2^{\cdot-}$, $\cdot OH$, H_2O_2 , and $^1O_2$. ROS are a normal byproduct of aerobic metabolism in plant cells, and various environmental stresses cause excessive ROS production. The peroxisomal photorespiration cycle, mitochondrial respiration, and chloroplastic photosynthesis are the three primary sources of ROS in plants. Although ROS have beneficial effects as essential signaling molecules in regulating

Table 12.3 Toxicological effects on some plant species due to exposure to metal-based nanomaterials (mNMs)

Metal-based nanomaterials	Source	Size	Dose	Plant	Application method	Effects	References
ZnONPs	Sigma-Aldrich, USA	100 nm	25–100 µg/ml	Onion (<i>Allium cepa</i>)	Root treatment	Pycnotic cells, micronuclei index, and chromosomal aberration index all increased with a reduction in mitotic index.	Kumari et al. (2011)
CuONPs and ZnONPs	Sigma-Aldrich (USA)	<50 nm and <100 nm, respectively.	500 mg Cu and Zn/kg	wheat (<i>Triticum aestivum</i>)	Plants were grown in sand containing NPs.	Oxidative stress, increased lipid peroxidation, increased oxidized glutathione, and decreased chlorophyll content.	Dimkpa et al. (2012)
AgNPs	Synthesis using NaBH ₄ + gum Arabic (GA) and polyvinylpyrrolidone (PVP) + ethylene glycol.	6 nm for GA coated and 20 nm for PVP coated.	10 mg/l	<i>Spirodela polyrhiza</i>	Placing <i>S. polyrhiza</i> colonies in the 10% Hoagland's solution with NPs.	Oxidative stress, effect on the structure and function of chloroplasts.	Jiang et al. (2014)
CuONPs	Sigma-Aldrich	<50 nm	5 mg/l	Rice (<i>Oryza sativa</i>)	Root treatment	Oxidative stress, intracellular metabolic disorders, DNA damage, destruction of certain genes, suppression of cell division, and inhibition of root growth.	Wang et al. (2015)
ZnONPs	Aladdin Corporation (Shanghai, China)	20–30 nm	10 and 50 mg/l	Tomato (<i>Solanum lycopersicum</i>)	Seedlings were placed on ½ MS culture media with NPs.	Oxidative stress	Li et al. (2016)
ZnONPs	Sigma-Aldrich (USA)	<50 nm	50–1000 µg/ml	Onion (<i>A. cepa</i>)	Plant roots were exposed to NPs solution.	Oxidative stress, mitochondrial depressive, and genotoxic effects.	Ahmed et al. (2017)

ZnONPs	Sigma-Aldrich (Germany)	<100 nm	225 mg/kg (Zn basis)	bean (<i>Phaseolus vulgaris</i>)	Soil treatment	Oxidative stress	García-Gómez et al. (2017)
ZnONPs	Synthesis using milk of <i>Calotropis gigantea</i> and Sigma-Aldrich (USA)	25.1 and 48.6 nm, respectively.	10–100 mg/l	grass pea (<i>Lathyrus sativus</i> L.)	Immersing the sprouting roots in different concentrations of NPs.	Oxidative stress and DNA damage.	Panda et al. (2017)
ZnNPs	Sigma (USA)	<100 nm	100–500 mg/l	Potato (<i>S. tuberosum</i>)	Foliar treatment	Oxidative stress	Raigond et al. (2017)
AgNPs	Synthesis using <i>Aloe vera</i> extract	47 nm	1 and 3 Mm	Mustard (<i>Brassica</i> sp.)	Seedlings were placed in a half-strength Hoagland solution with NPs.	Oxidative stress, DNA degradation, cell death.	Vishwakarma et al. (2017)
CuONPs	Sigma-Aldrich	30–40 nm	12 mg/l	Tobacco (<i>Nicotiana Tabacum</i>)	Exposure of tobacco cells to NPs.	Oxidative stress	Dai et al. (2018)
AgNPs	nanoCompositex®	10, 20, 51, and 73 nm	100 mg/l	Onion (<i>A. cepa</i>)	Seed treatment and exposure of seeds and radicles to NPs at the beginning of radicle emergence.	Cytotoxic and genotoxic effects increase with decreasing particle diameter and include effects on germination, mitosis, nuclear abnormality, and micronucleus index.	Scherer et al. (2019)
ZnONPs	Synthesis using <i>Ochradenus arabicus</i> shoot extract	16.56–19.65 nm	100–300 mg/l	<i>O. arabicus</i>	Regenerated shoots cultured on MS medium with NPs.	Oxidative stress	Al-Quraiby et al. (2021)
AgNPs	Synthesis using <i>Satureja khuzistanica</i> extract	10–50 nm	10 and 40 mg/l	Basil (<i>Ocimum basilicum</i>)	Germinated seeds were placed in different concentrations of NPs.	Oxidative stress	Zareei et al. (2023)

several plant developmental processes and increasing plant tolerance to biotic and abiotic stressors, excessive production of ROS damages cellular components, including nucleic acids, carbohydrates, proteins, and lipids. Antioxidant enzymes like SOD and CAT are required for scavenging ROS in various cell compartments and responding to stressful situations to protect plant cells from oxidative damage. Non-enzymatic defenses include ascorbate (AA), glutathione (GSH), and others. However, under high oxidative stress conditions, the antioxidant defense mechanism may become overloaded, resulting in cellular damage and death (Zandi & Schnug, 2022). Production of ROS and the occurrence of oxidative stress by mNMs have different degrees based on the sizes, shapes, chemical compositions, surface functionalization, surface chemistry, concentration, and other properties of the mNMs (Awashra & Mlynarz, 2023). A general expected no-effect concentration value of less than 10 mg/kg soil is proposed for oxidative stress in plants (considering lipid peroxidation as an endpoint) induced by many mNMs (Soares et al., 2018). The ability of a chemical or agent to cause damage to a cell's genetic information is known as genotoxicity (Ren et al., 2017). Exposure to high concentrations or prolonged exposure to NPs causes genotoxicity through direct mechanisms by passing through the cell membrane and nucleus and interacting directly with DNA. Genotoxicity also occurs indirectly as a result of the interaction of NPs with nuclear proteins or from oxidative stress caused by reactive oxygen species or through reduced DNA repair functions (Karami Mehrian & De Lima, 2016). Cytotoxicity is the ability of a molecule or a compound to cause damage to structures or fundamental processes for cell maintenance such as proliferation, survival, and normal biochemistry and physiology (León-Mejía et al., 2021).

12.5 Conclusion

Climate change exacerbates plant disease threats, particularly bacterial plant diseases, by increasing the likelihood of disease outbreaks and the development of new pathogenic strains. The use of conventional pesticides to manage bacterial plant diseases is fraught with potential risks, including harm to non-target organisms and the environment as well as the emergence of strains resistant to conventional pesticides. Therefore, the use of metal NPs to control bacteria, especially those resistant to conventional bactericides, and reduce toxicity to non-target organisms has become of great importance. Nanobactericides can provide an effective alternative against gram-positive and gram-negative bacteria as they act through several mechanisms, including interaction with the cell wall, membrane penetration, generation of ROS, DNA damage, suppression of protein synthesis, and others. Nanobactericides such as AgNPs, Cu-based NPs, and ZnONPs have shown promising antibacterial activity against several plant pathogenic bacteria. Experiments have shown that nanobactericides can be applied to control bacterial plant diseases in agricultural systems through various methods such as soil applications, plant spraying, and root dipping treatments. *R. solanacearum*, *P. carotovorum*, *P.*

atrosepticum, *Pseu. syringae*, *E. amylovora*, and *X. campestris* are examples of important bacterial pathogens that can be controlled using nanobactericides. Despite the beneficial aspects of using NPs on plants, caution should be exercised when using them, as excessive doses may reduce seed germination and biomass production, disrupt photosynthesis, induce oxidative stress, affect cell membrane integrity, change gene expression, damage DNA, and cause genetic variations in plants or other potential harm.

References

- Ahmad, A., Hashmi, S. S., Palma, J. M., & Corpas, F. J. (2022). Influence of metallic, metallic oxide, and organic nanoparticles on plant physiology. *Chemosphere*, 290, 133329. <https://doi.org/10.1016/j.chemosphere.2021.133329>
- Ahmed, B., Dwivedi, S., Abdin, M. Z., Azam, A., Al-Shaeri, M., Khan, M. S., Saquib, Q., Al-Khedhairi, A. A., & Musarrat, J. (2017). Mitochondrial and chromosomal damage induced by oxidative stress in Zn^{2+} ions, ZnO-Bulk and ZnO-NPs treated *Allium cepa* roots. *Scientific Reports*, 7, 40685. <https://doi.org/10.1038/srep40685>
- Alamer, I. S. A., Tomah, A. A., Ahmed, T., Li, B., & Zhang, J. (2022). Biosynthesis of silver chloride nanoparticles by rhizospheric bacteria and their antibacterial activity against phytopathogenic bacterium *Ralstonia solanacearum*. *Molecules*, 27, 224. <https://doi.org/10.3390/molecules27010224>
- Al-Qurainy, F., Khan, S., Alansi, S., Nadeem, M., Alshameri, A., Gaafar, A. R., Tarrour, M., Shaikhaldein, H. O., Salih, A. M., Alenezi, N. A., & Alfarraraj, N. S. (2021). Impact of phytomediated zinc oxide nanoparticles on growth and oxidative stress response of *in vitro* raised shoots of *Ochradenus arabicus*. *BioMed Research International*, 2021, 6829806. <https://doi.org/10.1155/2021/6829806>
- Awashra, M., & Mlynarz, P. (2023). The toxicity of nanoparticles and their interaction with cells: An *in vitro* metabolomic perspective. *Nanoscale Advances*, 5, 2674–2723. <https://doi.org/10.1039/d2na00534d>
- Baker, S., & Perianova, O. V. (2019). Bio-nanobactericides: An emanating class of nanoparticles towards combating multi-drug resistant pathogens. *SN Applied Sciences*, 1, 699. <https://doi.org/10.1007/s42452-019-0715-x>
- Bhagat, M., Anand, R., Sharma, P., Rajput, P., Sharma, N., & Singh, K. (2021). Review-multifunctional copper nanoparticles: Synthesis and applications. *ECS Journal of Solid State Science and Technology*, 10, 063011. <https://doi.org/10.1149/2162-8777/ac07f8>
- Bibi, Z., Ali, M., Abohashrh, M., Ahmad, I., Khan, H., Ali, M., Akbar, F., Ahmad, N., Iqbal, A., Ullah, F., Ullah, Z., & Muhmood, T. (2023). Biologically synthesized silver nanoparticles efficiently control plant pathogenic bacteria-*Erwinia carotovora* and *Ralstonia solanacearum*. *Inorganics*, 11, 309. <https://doi.org/10.3390/inorganics11070309>
- Brandelli, A., Ritter, A. C., & Veras, F. F. (2017). Antimicrobial activities of metal nanoparticles. In M. Rai & R. Shegokar (Eds.), *Metal nanoparticles in pharma* (pp. 337–363). Springer. https://doi.org/10.1007/978-3-319-63790-7_15
- Chen, J., Li, S., Luo, J., Wang, R., & Ding, W. (2016). Enhancement of the antibacterial activity of silver nanoparticles against phytopathogenic bacterium *Ralstonia solanacearum* by stabilization. *Journal of Nanomaterials*, 2016, 135852. <https://doi.org/10.1155/2016/7135852>
- Chen, J., Mao, S., Xu, Z., & Ding, W. (2019). Various antibacterial mechanisms of biosynthesized copper oxide nanoparticles against soilborne *Ralstonia solanacearum*. *RSC Advances*, 9, 3788–3799. <https://doi.org/10.1039/c8ra09186b>

- Chen, Y., Lu, J., Liu, M., Li, H., Sun, Q., Nechitaylo, G. S., Bogoslovskaya, O. A., Olkhovskaya, I. P., & Glushchenko, N. N. (2020). Tomato response to metal nanoparticles introduction into the nutrient medium. *IET Nanobiotechnology*, 14(5), 382–388. <https://doi.org/10.1049/iet-nbt.2019.0183>
- Chen, Z., Chu, Z., Jiang, Y., Xu, L., Qian, H., Wang, Y., & Wang, W. (2023). Recent advances on nanomaterials for antibacterial treatment of oral diseases. *Materials Today Bio*, 20, 100635. <https://doi.org/10.1016/j.mtbio.2023.100635>
- Chowdhury, S., Basu, A., & Kundu, S. (2014). Green synthesis of protein capped silver nanoparticles from phytopathogenic fungus *Macrophomina phaseolina* (Tassi) Goid with antimicrobial properties against multidrug-resistant bacteria. *Nanoscale Research Letters*, 9, 365. <https://doi.org/10.1186/1556-276X-9-365>
- Chowdhury, A. R., Kumar, R., Mahanty, A., Mukherjee, K., Kumar, S., Tribhuvan, K. U., Sheel, R., Lenka, S., Singh, B. K., Chattopadhyay, C., Sharma, T. R., Bhadana, V. P., & Sarkar, B. (2024). Inhibitory role of copper and silver nanocomposite on important bacterial and fungal pathogens in rice (*Oryza sativa*). *Scientific Reports*, 14, 1779. <https://doi.org/10.1038/s41598-023-49918-0>
- Coelho, F. C., Squitti, R., Ventriglia, M., Cerchiaro, G., Daher, J. P., Rocha, J. G., Rongioletti, M. C. A., & Moonen, A. C. (2020). Agricultural use of copper and its link to Alzheimer's disease. *Biomolecules*, 10, 897. <https://doi.org/10.3390/biom10060897>
- Córdova, P., Rivera-González, J. P., Rojas-Martínez, V., Fiore, N., Bastías, R., Zamorano, A., Vera, F., Barreto, J., Díaz, B., Ilabaca-Díaz, C., Bertaccini, A., & Higuera, G. (2023). Phytopathogenic *Pseudomonas syringae* as a threat to agriculture: Perspectives of a promising biological control using bacteriophages and microorganisms. *Horticulturae*, 9, 712. <https://doi.org/10.3390/horticulturae9060712>
- Czajkowski, R., Pérombelon, M. C. M., Van Veen, J. A., & Van der Wolf, J. M. (2011). Control of blackleg and tuber soft rot of potato caused by *Pectobacterium* and *Dickeya* species: A review. *Plant Pathology*, 60, 999–1013. <https://doi.org/10.1111/j.1365-3059.2011.02470.x>
- Dai, Y., Wang, Z., Zhao, J., Xu, L., Xu, L., Yu, X., Wei, Y., & Xing, B. (2018). Interaction of CuO nanoparticles with plant cells: Internalization, oxidative stress, electron transport chain disruption, and toxicogenomic responses. *Environmental Science: Nano*, 5, 2269–2281. <https://doi.org/10.1039/c8en00222c>
- Dakal, T. C., Kumar, A., Majumdar, R. S., & Yadav, V. (2016). Mechanistic basis of antimicrobial actions of silver nanoparticles. *Frontiers in Microbiology*, 7, 1831. <https://doi.org/10.3389/fmicb.2016.01831>
- Dilbar, S., Sher, H., Ali, H., Ullah, R., Ali, A., & Ullah, Z. (2023). Antibacterial efficacy of green synthesized silver nanoparticles using *Salvia nubicola* extract against *Ralstonia solanacearum*, the causal agent of vascular wilt of tomato. *ACS Omega*, 8, 31155–31167. <https://doi.org/10.1021/acsomega.3c03164>
- Dimkpa, C. O., McLean, J. E., Latta, D. E., Manangón, E., Britt, D. W., Johnson, W. P., Boyanov, M. I., & Anderson, A. J. (2012). CuO and ZnO nanoparticles: Phytotoxicity, metal speciation, and induction of oxidative stress in sand-grown wheat. *Journal of Nanoparticle Research*, 14, 1125. <https://doi.org/10.1007/s11051-012-1125-9>
- Doolotkeldieva, T., Bobusheva, S., Zhasnakunov, Z., & Satybaldiev, A. (2022). Biological activity of Ag and Cu monometallic nanoparticles and Ag-Cu bimetallic nanocomposites against plant pathogens and seeds. *Journal of Nanomaterials*, 2022, 190280. <https://doi.org/10.1155/2022/1190280>
- El-Batal, A. I., Balabel, N. M., Attia, M. S., & El-Sayyad, G. S. (2020). Antibacterial and antibiofilm potential of mono-dispersed stable copper oxide nanoparticles-streptomycin nano-drug: Implications for some potato plant bacterial pathogen treatment. *Journal of Cluster Science*, 31, 1021–1040. <https://doi.org/10.1007/s10876-019-01707-4>
- Fan, G., Xiao, Q., Li, Q., Xia, Y., Feng, H., Ma, X., Cai, L., & Sun, X. (2023). Antimicrobial mechanisms of ZnO nanoparticles to phytopathogen *Pseudomonas syringae*: Damage of cell envelope, suppression of metabolism, biofilm and motility, and stimulation of stomatal

- immunity on host plant. *Pesticide Biochemistry and Physiology*, 194, 105455. <https://doi.org/10.1016/j.pestbp.2023.105455>
- García-Gómez, C., Obrador, A., González, D., Babín, M., & Fernández, M. D. (2017). Comparative effect of ZnO NPs, ZnO bulk and ZnSO₄ in the antioxidant defences of two plant species growing in two agricultural soils under greenhouse conditions. *Science of the Total Environment*, 589, 11–24. <https://doi.org/10.1016/j.scitotenv.2017.02.153>
- García-López, J. I., Niño-Medina, G., Olivares-Sáenz, E., Lira-Saldivar, R. H., Barriga-Castro, E. D., Vázquez-Alvarado, R., Rodríguez-Salinas, P. A., & Zavala-García, F. (2019). Foliar application of zinc oxide nanoparticles and zinc sulfate boosts the content of bioactive compounds in habanero peppers. *Plants*, 8(8), 254. <https://doi.org/10.3390/plants8080254>
- Geremew, A., Carson, L., Wollesenbet, S., Wang, H., Reeves, S., Jr., Saganti, P., Weerasooriya, A., & Peace, E. (2023). Effect of zinc oxide nanoparticles synthesized from *Carya illinoensis* leaf extract on growth and antioxidant properties of mustard (*Brassica juncea*). *Frontiers in Plant Science*, 14, 1108186. <https://doi.org/10.3389/fpls.2023.1108186>
- Ghazy, N. A., Abd El-Hafez, O. A., El-Bakery, A. M., & El-Geddawy, D. I. H. (2021). Impact of silver nanoparticles and two biological treatments to control soft rot disease in sugar beet (*Beta vulgaris* L). *Egyptian Journal of Biological Pest Control*, 31(3). <https://doi.org/10.1186/s41938-020-00347-5>
- Girma, A. (2023). Alternative mechanisms of action of metallic nanoparticles to mitigate the global spread of antibiotic-resistant bacteria. *The Cell Surface*, 10, 100112. <https://doi.org/10.1016/j.tcs.2023.100112>
- Gkanatsiou, C., Karamanoli, K., Menkissoglu-Spiroudi, U., & Dendrinou-Samara, C. (2019). Composition effect of Cu-based nanoparticles on phytopathogenic bacteria. Antibacterial studies and phytotoxicity evaluation. *Polyhedron*, 170, 395–403. <https://doi.org/10.1016/j.poly.2019.06.002>
- Goswami, P., Yadav, S., & Mathur, J. (2019). Positive and negative effects of nanoparticles on plants and their applications in agriculture. *Plant Science Today*, 6(2), 232–242. <https://doi.org/10.14719/pst.2019.6.2.502>
- Gowtham, H. G., Shilpa, N., Singh, S. B., Aiyaz, M., Abhilash, M. R., Nataraj, K., Amruthesh, K. N., Ansari, M. A., Alomary, M. N., & Murali, M. (2024). Toxicological effects of nanoparticles in plants: Mechanisms involved at morphological, physiological, biochemical and molecular levels. *Plant Physiology and Biochemistry*, 210, 108604. <https://doi.org/10.1016/j.plaphy.2024.108604>
- Guilger-Casagrande, M., Bilesky-José, N., Sousa, B. T., Oliveira, H. C., Fraceto, L. F., & Lima, R. (2022). Effects of biogenic silver and iron nanoparticles on soybean seedlings (*Glycine max*). *BMC Plant Biology*, 22, 255. <https://doi.org/10.1186/s12870-022-03638-1>
- Islam, T., Haque, M. A., Barai, H. R., Istiaq, A., & Kim, J. J. (2024). Antibiotic resistance in plant pathogenic bacteria: Recent data and environmental impact of unchecked use and the potential of biocontrol agents as an eco-friendly alternative. *Plants*, 13, 1135. <https://doi.org/10.3390/plants13081135>
- Jaithon, T., Ruangtong, J., T-Thienprasert, J., & T-Thienprasert, N. P. (2022). Effects of waste-derived ZnO nanoparticles against growth of plant pathogenic bacteria and epidermoid carcinoma cells. *Crystals*, 12, 779. <https://doi.org/10.3390/cryst12060779>
- Jiang, H. S., Qiu, X. N., Li, G. B., Li, W., & Yin, L. Y. (2014). Silver nanoparticles induced accumulation of reactive oxygen species and alteration of antioxidant systems in the aquatic plant *Spirodela polyrhiza*. *Environmental Toxicology and Chemistry*, 33(6), 1398–1405. <https://doi.org/10.1002/etc.2577>
- Joudeh, N., & Linke, D. (2022). Nanoparticle classification, physicochemical properties, characterization, and applications: A comprehensive review for biologists. *Journal of Nanobiotechnology*, 20, 262. <https://doi.org/10.1186/s12951-022-01477-8>
- Kalisz, A., Kornaś, A., Skoczowski, A., Oliwa, J., Jurkow, R., Gil, J., Sękara, A., Sałata, A., & Caruso, G. (2023). Leaf chlorophyll fluorescence and reflectance of oakleaf lettuce exposed to metal and metal (oid) oxide nanoparticles. *BMC Plant Biology*, 23, 329. <https://doi.org/10.1186/s12870-023-04305-9>

- Kandhol, N., Singh, V. P., White, J. C., Tran, L. S. P., & Tripathi, D. K. (2022). Plant growth hormones and nanomaterial interface: Exploring the connection from development to defense. *Plant and Cell Physiology*, 63(12), 1840–1847. <https://doi.org/10.1093/pcp/pcac147>
- Karami Mehrian, S., & De Lima, R. (2016). Nanoparticles cyto and genotoxicity in plants: Mechanisms and abnormalities. *Environmental Nanotechnology, Monitoring and Management*, 6, 184–193. <https://doi.org/10.1016/j.enmm.2016.08.003>
- Khan, R. A. A., Tang, Y., Naz, I., Alam, S. S., Wang, W., Ahmad, M., Najeeb, S., Rao, C., Li, Y., Xie, B., & Li, Y. (2021). Management of *Ralstonia solanacearum* in tomato using ZnO nanoparticles synthesized through *Matricaria chamomilla*. *Plant Disease*, 105(10), 3224–3230. <https://doi.org/10.1094/PDIS-08-20-1763-RE>
- Khan, M., Khan, A. A., Parveen, A., Min, K., Yadav, V. K., Khan, A. U., & Alam, M. (2023a). Mitigating the growth of plant pathogenic bacterium, fungi, and nematode by using plant-mediated synthesis of copper oxide nanoparticles (CuO NPs). *Green Chemistry Letters and Reviews*, 16(1), 2177520. <https://doi.org/10.1080/17518253.2023.2177520>
- Khan, S., Al-qurainy, F., Al-hashimi, A., Nadeem, M., Tarroum, M., Shaikhaldain, H. O., & Salih, A. M. (2023b). Effect of green synthesized ZnO-NPs on growth, antioxidant system response and bioactive compound accumulation in *Echinops macrochaetus*, a potential medicinal plant, and assessment of genome size (2C DNA content). *Plants*, 12, 1669. <https://doi.org/10.3390/plants12081669>
- Khan, A., Ahmad, N., Fazal, H., Ali, M., Akbar, F., Khan, I., Tayyab, M., Uddin, M. N., Ahmad, N., Abdel-Maksoud, M. A., Saleh, I. A., Zomot, N., AbdElgawad, H., Rauf, K., Iqbal, B., Teixeira Filho, M. C. M., El-Tayeb, M. A., & Jalal, A. (2024). Biogenic synthesis of silver nanoparticles using *Rubus fruticosus* extract and their antibacterial efficacy against *Erwinia caratovora* and *Ralstonia solanacearum* phytopathogens. *RSC Advances*, 14, 5754–5763. <https://doi.org/10.1039/d3ra06723h>
- Kim, D. Y., Patel, S. K. S., Rasool, K., Lone, N., Bhatia, S. K., Seth, C. S., & Ghodake, G. S. (2024). Bioinspired silver nanoparticle-based nanocomposites for effective control of plant pathogens: A review. *Science of the Total Environment*, 908, 168318. <https://doi.org/10.1016/j.scitotenv.2023.168318>
- Kőrösi, L., Pertics, B., Schneider, G., Bognár, B., Kovács, J., Meynen, V., Scarpellini, A., Pasquale, L., & Prato, M. (2020). Photocatalytic inactivation of plant pathogenic bacteria using TiO₂ nanoparticles prepared hydrothermally. *Nanomaterials*, 10, 1730. <https://doi.org/10.3390/nano10091730>
- Kumari, M., Khan, S. S., Pakrashi, S., Mukherjee, A., & Chandrasekaran, N. (2011). Cytogenetic and genotoxic effects of zinc oxide nanoparticles on root cells of *Allium cepa*. *Journal of Hazardous Materials*, 190, 613–621. <https://doi.org/10.1016/j.jhazmat.2011.03.095>
- León-Mejía, G., Guevara, A. M., Moreno, O. F., & Cruz, C. U. (2021). Cytotoxicity as a fundamental response to xenobiotics. In S. Soloneski & M. L. Larramendy (Eds.), *Cytotoxicity - new insights into toxic assessment*. IntechOpen. <https://doi.org/10.5772/intechopen.96239>
- Li, M., Ahammed, G. J., Li, C., Bao, X., Yu, J., Huang, C., Yin, H., & Zhou, J. (2016). Brassinosteroid ameliorates zinc oxide nanoparticles-induced oxidative stress by improving antioxidant potential and redox homeostasis in tomato seedling. *Frontiers in Plant Science*, 7, 615. <https://doi.org/10.3389/fpls.2016.00615>
- Li, P., Xia, Y., Song, K., & Liu, D. (2024). The impact of nanomaterials on photosynthesis and antioxidant mechanisms in Gramineae plants: Research progress and future prospects. *Plants*, 13, 984. <https://doi.org/10.3390/plants13070984>
- Luong, H. T., Nguyen, C. X., Lam, T. T., Nguyen, T. H., Le Dang, Q., Lee, J. H., Hur, H. G., Nguyen, H. T., & Ho, C. T. (2022). Antibacterial effect of copper nanoparticles produced in a *Shewanella*-supported non-external circuit bioelectrical system on bacterial plant pathogens. *RSC Advances*, 12, 4428–4436. <https://doi.org/10.1039/d1ra08187j>
- Ma, X., Zhou, S., Xu, X., & Du, Q. (2022). Copper-containing nanoparticles: Mechanism of antimicrobial effect and application in dentistry-a narrative review. *Frontiers in Surgery*, 9, 905892. <https://doi.org/10.3389/fsurg.2022.905892>

- Majeed, M., Hakeem, K. R., & Rehman, R. U. (2022). Synergistic effect of plant extract coupled silver nanoparticles in various therapeutic applications- present insights and bottlenecks. *Chemosphere*, 288(P2), 132527. <https://doi.org/10.1016/j.chemosphere.2021.132527>
- Makarovskiy, D., Fadeev, L., Salam, B. B., Zelinger, E., Matan, O., Inbar, J., Jurkevitch, E., Gozin, M., & Burdman, S. (2018). Silver nanoparticles complexed with bovine submaxillary mucin possess strong antibacterial activity and protect against seedling infection. *Applied and Environmental Microbiology*, 84(4), e02212–17. <https://doi.org/10.1128/AEM.02212-17>
- Mawale, K. S., Nandini, B., & Giridhar, P. (2024). Copper and silver nanoparticle seed priming and foliar spray modulate plant growth and thrips infestation in *Capsicum* spp. *ACS Omega*, 9, 3430–3444. <https://doi.org/10.1021/acsomega.3c06961>
- Miller, S. A., Ferreira, J. P., & LeJeune, J. T. (2022). Antimicrobial use and resistance in plant agriculture: A one health perspective. *Agriculture*, 12, 289. <https://doi.org/10.3390/agriculture12020289>
- Nafees, M., Ali, S., Rizwan, M., Aziz, A., Adrees, M., Hussain, S. M., Ali, Q., & Junaid, M. (2020). Effect of nanoparticles on plant growth and physiology and on soil microbes. In I. Bhushan, V. Singh, & D. Tripathi (Eds.), *Nanomaterials and environmental biotechnology, nanotechnology in the life sciences* (pp. 65–85). Springer. https://doi.org/10.1007/978-3-030-34544-0_5
- Noori, A., Ngo, A., Gutierrez, P., Theberge, S., & White, J. C. (2020). Silver nanoparticle detection and accumulation in tomato (*Lycopersicon esculentum*). *Journal of Nanoparticle Research*, 22, 131. <https://doi.org/10.1007/s11051-020-04866-y>
- Orfei, B., Moretti, C., Loreti, S., Tatulli, G., Onofri, A., Scotti, L., Aceto, A., & Buonauro, R. (2023). Silver nanoclusters with Ag^{2+/3+} oxidative states are a new highly effective tool against phytopathogenic bacteria. *Applied Microbiology and Biotechnology*, 107, 4519–4531. <https://doi.org/10.1007/s00253-023-12596-z>
- Panda, K. K., Golari, D., Venugopal, A., Achary, V. M. M., Phaomei, G., Parinandi, N. L., Sahu, H. K., & Panda, B. B. (2017). Green synthesized zinc oxide (ZnO) nanoparticles induce oxidative stress and DNA damage in *Lathyrus sativus* L. root bioassay system. *Antioxidants*, 6, 35. <https://doi.org/10.3390/antiox6020035>
- Pandya, P., Kumar, S., Patil, G., Mankad, M., & Shah, Z. (2024). Impact of ZnO nanoprimer on physiological and biochemical traits of wheat (*Triticum aestivum* L.) seedling. *CABI Agriculture and Bioscience*, 5, 27. <https://doi.org/10.1186/s43170-024-00228-z>
- Pasquet, J., Chevalier, Y., Pelletier, J., Couval, E., Bouvier, M. A. (2014). The contribution of zinc ions to the antimicrobial activity of zinc oxide. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 457, 263–274. <https://doi.org/10.1016/j.colsurfa.2014.05.057>
- Pelegrino, M. T., Kohatsu, M. Y., Seabra, A. B., Monteiro, L. R., Gomes, D. G., Oliveira, H. C., Rolim, W. R., De Jesus, T. A., Batista, B. L., & Lange, C. N. (2020). Effects of copper oxide nanoparticles on growth of lettuce (*Lactuca sativa* L.) seedlings and possible implications of nitric oxide in their antioxidative defense. *Environmental Monitoring and Assessment*, 192, 232. <https://doi.org/10.1007/s10661-020-8188-3>
- Rabea, A., Naeem, E., Balabel, N. M., & Daigham, G. E. (2023). Management of potato brown rot disease using chemically synthesized CuO-NPs and MgO-NPs. *Botanical Studies*, 64, 20. <https://doi.org/10.1186/s40529-023-00393-w>
- Raigond, P., Raigond, B., Kaundal, B., Singh, B., Joshi, A., & Dutt, S. (2017). Effect of Zn nanoparticles on antioxidative system of potato plants. *Journal of Environmental Biology*, 38, 435–439. <https://doi.org/10.22438/jeb/38/3/MS-209>
- Rana, A., Kumari, A., Chaudhary, A. K., Srivastava, R., Kamil, D., Vashishtha, P., & Sharma, S. N. (2023). An investigation of antimicrobial activity for plant pathogens by green-synthesized silver nanoparticles using *Azadirachta indica* and *Mangifera indica*. *Physchem*, 3, 125–146. <https://doi.org/10.3390/physchem3010010>
- Rashid, M. U., Shah, S. J., Attacha, S., Khan, L., Saeed, J., Shah, S. T., & Mohamed, H. I. (2024). Green synthesis and characterization of zinc oxide nanoparticles using *Citrus limetta* peels

- extract and their antibacterial activity against brown and soft rot pathogens and antioxidant potential. *Waste and Biomass Valorization*, 15, 3351–3366. <https://doi.org/10.1007/s12649-023-02389-w>
- Ren, N., Atyah, M., Chen, W. Y., & Zhou, C. H. (2017). The various aspects of genetic and epigenetic toxicology: Testing methods and clinical applications. *Journal of Translational Medicine*, 15, 110. <https://doi.org/10.1186/s12967-017-1218-4>
- Rónavári, A., Béteky, P., Boka, E., Zakupszky, D., Igaz, N., Szerencsés, B., Pfeiffer, I., Kónya, Z., & Kiricsi, M. (2021). Polyvinyl-pyrrolidone-coated silver nanoparticles—The colloidal, chemical and biological consequences of steric stabilization under biorelevant conditions. *International Journal of Molecular Sciences*, 22, 8673. <https://doi.org/10.3390/ijms22168673>
- Sadak, M. S. (2019). Impact of silver nanoparticles on plant growth , some biochemical aspects , and yield of fenugreek plant (*Trigonella foenum- graecum*). *Bulletin of the National Research Centre*, 43, 38. <https://doi.org/10.1186/s42269-019-0077-y>
- Salah, I., Parkin, I. P., & Allan, E. (2021). Copper as an antimicrobial agent: Recent advances. *RSC Advances*, 11, 18179–18186. <https://doi.org/10.1039/d1ra02149d>
- Scherer, M. D., Sposito, J. C. V., Falco, W. F., Grisolia, A. B., Andrade, L. H. C., Lima, S. M., Machado, G., Nascimento, V. A., Gonçalves, D. A., Wender, H., Oliveira, S. L., & Caires, A. R. L. (2019). Cytotoxic and genotoxic effects of silver nanoparticles on meristematic cells of *Allium cepa* roots: A close analysis of particle size dependence. *Science of the Total Environment*, 660, 459–467. <https://doi.org/10.1016/j.scitotenv.2018.12.444>
- Shahraki, S. H., Javar, F. M., Jamali, B., & Sargazi, F. (2024). Beneficial role of coronatine on the morphological and physiological responses of cress plants (*Lepidium sativum*) exposed to silver nanoparticle. *Botanical Studies*, 65, 17. <https://doi.org/10.1186/s40529-024-00425-z>
- Shaikhaldein, H. O., Al Qurainy, F., Nadeem, M., Khan, S., Tarroum, M., & Salih, A. M. (2020). Biosynthesis and characterization of silver nanoparticles using *Ochradenus arabicus* and their physiological effect on *Maerua oblongifolia* raised in vitro. *Scientific Reports*, 10, 17569. <https://doi.org/10.1038/s41598-020-74675-9>
- Shang, Y., Hasan, M. K., Ahammed, G. J., Li, M., & Yin, H. (2019). Applications of nanotechnology in plant growth and crop protection: A review. *Molecules*, 24, 2558. <https://doi.org/10.3390/molecules24142558>
- Shaw, J. L. A., Ernakovich, J. G., Judy, J. D., Farrell, M., Whatmuff, M., & Kirby, J. (2020). Long-term effects of copper exposure to agricultural soil function and microbial community structure at a controlled and experimental field site. *Environmental Pollution*, 263, 114411. <https://doi.org/10.1016/j.envpol.2020.114411>
- Shoeib, A. A., Ashmawy, N. A., Kamal, A., & Zaki, S. A. E. F. (2023). Nano-metals forming bacteria in Egypt. II. Efficacy towards biomolecules, ultrastructure, growth parameters, and eco-friendly therapeutic of soft rot/blackleg genera. *Microbial Cell Factories*, 22, 101. <https://doi.org/10.1186/s12934-023-02101-6>
- Siddiqui, Z. A., Khan, A., Khan, M. R., & Abd-Allah, E. F. (2018). Effects of zinc oxide nanoparticles (ZnONPs) and some plant pathogens on the growth and nodulation of lentil (*lens culinaris* medik.). *Acta Phytopathologica et Entomologica Hungarica*, 53(2), 195–212. <https://doi.org/10.1556/038.53.2018.012>
- Singh, R., Patade, V. Y., Sanchita, & Singh, A. (2021). Antimicrobial potential of silver nanoparticles biosynthesized using aerial yam bulbils for control of selected phytopathogens. *Archives of Phytopathology and Plant Protection*, 54(19–20), 2275–2293. <https://doi.org/10.1080/03235408.2021.1929690>
- Singh, B. K., Delgado-Baquerizo, M., Egidi, E., Guirado, E., Leach, J. E., Liu, H., & Trivedi, P. (2023a). Climate change impacts on plant pathogens, food security and paths forward. *Nature Reviews Microbiology*, 21, 640–656. <https://doi.org/10.1038/s41579-023-00900-7>
- Singh, D., Jain, D., Rajpurohit, D., Jat, G., Kushwaha, H. S., Singh, A., Mohanty, S. R., Al-Sadoon, M. K., Zaman, W., & Upadhyay, S. K. (2023b). Bacteria assisted green synthesis of copper oxide nanoparticles and their potential applications as antimicrobial agents and plant growth stimulants. *Frontiers in Chemistry*, 11, 1154128. <https://doi.org/10.3389/fchem.2023.1154128>

- Sirelkhatim, A., Mahmud, S., Seeni, A., Kaus, N. H. M., Ann, L. C., Bakhori, S. K. M., Hasan, H., & Mohamad, D. (2015). Review on zinc oxide nanoparticles : Antibacterial activity and toxicity mechanism. *Nano-Micro Letters*, 7(3), 219–242. <https://doi.org/10.1007/s40820-015-0040-x>
- Smiechowicz, E., Niekraszewicz, B., & Kulpinski, P. (2021). Optimisation of AgNP synthesis in the production and modification of antibacterial cellulose fibres. *Materials*, 14, 4126. <https://doi.org/10.3390/ma14154126>
- Soares, C., Pereira, R., & Fidalgo, F. (2018). Metal-based nanomaterials and oxidative stress in plants: Current aspects and overview. In M. Faisal, Q. Saquib, A. A. Alatar, & A. A. Al-Khedhairi (Eds.), *Phytotoxicity of nanoparticles* (pp. 197–227). Springer. https://doi.org/10.1007/978-3-319-76708-6_8
- Srivastav, A., Ganjewala, D., Singhal, R. K., Rajput, V. D., Minkina, T., Voloshina, M., Srivastava, S., & Shrivastava, M. (2021). Effect of ZnO nanoparticles on growth and biochemical responses of wheat and maize. *Plants*, 10, 2556. <https://doi.org/10.3390/plants10122556>
- Tessema, G. L., & Seid, H. E. (2023). Potato bacterial wilt in Ethiopia: History, current status, and future perspectives. *PeerJ*, 11, e14661. <https://doi.org/10.7717/peerj.14661>
- Thiruvengadam, M., Chi, H. Y., & Kim, S. H. (2024). Impact of nanopollution on plant growth, photosynthesis, toxicity, and metabolism in the agricultural sector: An updated review. *Plant Physiology and Biochemistry*, 207, 108370. <https://doi.org/10.1016/j.plaphy.2024.108370>
- Tripathi, D., Singh, M., & Pandey-Rai, S. (2022). Crosstalk of nanoparticles and phytohormones regulate plant growth and metabolism under abiotic and biotic stress. *Plant Stress*, 6, 100107. <https://doi.org/10.1016/j.stress.2022.100107>
- Trzcńska-Wencel, J., Wypij, M., Terzyk, A. P., Rai, M., & Golińska, P. (2023). Biofabrication of novel silver and zinc oxide nanoparticles from *Fusarium solani* IOR 825 and their potential application in agriculture as biocontrol agents of phytopathogens, and seed germination and seedling growth promoters. *Frontiers in Chemistry*, 11, 1235437. <https://doi.org/10.3389/fchem.2023.1235437>
- Usman, O., Mohsin Baig, M. M., Ikram, M., Iqbal, T., Islam, S., Syed, W., Al-Rawi, M. B. A., & Naseem, M. (2024). Green synthesis of metal nanoparticles and study their anti-pathogenic properties against pathogens effect on plants and animals. *Scientific Reports*, 14, 11354. <https://doi.org/10.1038/s41598-024-61920-8>
- Varympopi, A., Dimopoulou, A., Theologidis, I., Karamanidou, T., Kerou, A. K., Vlachou, A., Karfaridis, D., Papafotis, D., Hatzinikolaou, D. G., Tsouknidas, A., & Skandalis, N. (2020). Bactericides based on copper nanoparticles restrain growth of important plant pathogens. *Pathogens*, 9, 1024. <https://doi.org/10.3390/pathogens9121024>
- Varympopi, A., Dimopoulou, A., Papafotis, D., Avramidis, P., Sarris, I., Karamanidou, T., Kerou, A. K., Vlachou, A., Vellis, E., Giannopoulos, A., Haralampidis, K., Theologidis, I., Hatzinikolaou, D. G., Tsouknidas, A., & Skandalis, N. (2022). Antibacterial activity of copper nanoparticles against *Xanthomonas campestris* pv. *vesicatoria*, causing leaf spot on tomato. *International Journal of Molecular Sciences*, 23, 4080. <https://doi.org/10.3390/ijms23084080>
- Vignardi, C. P., Muller, E. B., Tran, K., Couture, J. L., Means, J. C., Murray, J. L. S., Ortiz, C., Keller, A. A., Smith Sanchez, N., & Lenihan, H. S. (2020). Conventional and nano-copper pesticides are equally toxic to the estuarine amphipod *Leptocheirus plumulosus*. *Aquatic Toxicology*, 224, 105481. <https://doi.org/10.1016/j.aquatox.2020.105481>
- Vishwakarma, K., Shweta, U. N., Singh, J., Liu, S., Singh, V. P., Prasad, S. M., Chauhan, D. K., Tripathi, D. K., & Sharma, S. (2017). Differential phytotoxic impact of plant mediated silver nanoparticles (AgNPs) and silver nitrate (AgNO₃) on *Brassica* sp. *Frontiers in Plant Science*, 8, 1501. <https://doi.org/10.3389/fpls.2017.01501>
- Wahab, S., Salman, A., Khan, Z., Khan, S., Krishnaraj, C., & Yun, S.-I. (2023). Metallic nanoparticles: A promising arsenal against antimicrobial resistance—Unraveling mechanisms and enhancing medication efficacy. *International Journal of Molecular Sciences*, 24, 14897. <https://doi.org/10.3390/ijms241914897>

- Wang, S., Liu, H., Zhang, Y., & Xin, H. (2015). The effect of CuONPs on reactive oxygen species and cell cycle gene expression in roots of rice. *Environmental Toxicology and Chemistry*, 34(3), 554–561. <https://doi.org/10.1002/etc.2826>
- Xalxo, R., Yadu, B., Chandrakar, V., Kumar, M., Chandra, J., & Keshavkant, S. (2021). Silver nanoparticles and their morpho-physiological responses on plants. In V. P. Singh, S. Singh, D. K. Tripathi, S. M. Prasad, & D. K. Chauhan (Eds.), *Plant responses to Nanomaterials. Nanotechnology in the life sciences* (pp. 183–216). Springer. https://doi.org/10.1007/978-3-030-36740-4_8
- Yadav, N., Garg, V. K., Chhillar, A. K., & Rana, J. S. (2023). Recent advances in nanotechnology for the improvement of conventional agricultural systems: A review. *Plant Nano Biology*, 4, 100032. <https://doi.org/10.1016/j.plana.2023.100032>
- Yang, Z., Xiao, Y., Jiao, T., Zhang, Y., Chen, J., & Gao, Y. (2020). Effects of copper oxide nanoparticles on the growth of rice (*Oryza sativa* L.) seedlings and the relevant physiological responses. *International Journal of Environmental Research and Public Health*, 17, 1260. <https://doi.org/10.3390/ijerph17041260>
- Zaki, S. A. E. F., Kamal, A., Ashmawy, N. A., & Shoeib, A. A. (2021). Nano-metals forming bacteria in Egypt. I. Synthesis, characterization and effect on some phytopathogenic bacteria *in vitro*. *Scientific Reports*, 11, 12876. <https://doi.org/10.1038/s41598-021-92171-6>
- Zandi, P., & Schnug, E. (2022). Reactive oxygen species, antioxidant responses and implications from a microbial modulation perspective. *Biology*, 11, 155. <https://doi.org/10.3390/biology11020155>
- Zareei, A., Abbaspour, H., Peyvandi, M., & Majd, A. (2023). Oxidative stress responses and toxicity of green synthesized silver nanoparticles (AgNPs) on basil (*Ocimum basilicum*) seedlings. *Journal of Chemical Health Risks*, 13(4), 691–699. <https://doi.org/10.22034/jchr.2023.1978538.1673>
- Zhang, S., Lin, L., Huang, X., Lu, Y. G., Zheng, D. L., & Feng, Y. (2022). Antimicrobial properties of metal nanoparticles and their oxide materials and their applications in oral biology. *Journal of Nanomaterials*, 2022, 063265. <https://doi.org/10.1155/2022/2063265>
- Ziotti, A. B. S., Ottoni, C. A., Correa, C. N., de Almeida, O. J. G., de Souza, A. O., & Neto, M. C. L. (2021). Differential physiological responses of a biogenic silver nanoparticle and its production matrix silver nitrate in *Sorghum bicolor*. *Environmental Science and Pollution Research*, 28, 32669–32682. <https://doi.org/10.1007/s11356-021-13069-4>

Chapter 13

Silver Nanoparticles: Synthesis, Characterization and Biological Applications



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Abstract Fungal pathogens pose a significant threat to crop yield and quality, leading to considerable losses in agricultural productivity. In response, synthetic chemical pesticides are often used to control these diseases and manage pest populations. The widespread application of these pesticides has led to several adverse environmental effects, which present serious challenges to the sustainable advancement of agriculture. In this context, advances in nanotechnology offer new opportunities for managing fungal diseases in plants. Silver nanoparticles (AgNPs) are renowned for their antimicrobial properties in biomedical applications. These nanoparticles can help combat fungal infestations in plants, potentially reducing the reliance on chemical pesticides and addressing antibiotic resistance. Despite their advantages, the use of AgNPs presents challenges, including potential soil and water contamination and variability in size and morphology due to different synthesis methods. In this context, this chapter aims to explore key aspects of AgNPs, including their synthesis, characterization, and antifungal properties. Moreover, this chapter provides an overview of the potential applications of AgNPs and discusses the challenges faced in developing new applications to promote sustainable and resilient agricultural practices for managing fungal infestations in plants.

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13.1 Introduction

The advances in nanotechnology impacted the course of the scientific world so that new paths became possible to create new alternatives for numerous areas. The high area-to-volume ratio and permeability of nanomaterials allow their investigation for the treatment of several pathologies in different biological systems (Brandelli, 2020). One example is the prominent development of nanotechnology in the medical field, generating new alternatives for treating diseases, and improving their effectiveness and quality of life for patients (Silva et al., 2023). However, nanotechnology also positively impacted plant systems.

The application of nanotechnology in plant sciences helps to improve nutrition, remediation of diseases, soil quality, and crop production, for instance, as reported in several studies throughout the decades. Thus, the use of nanotechnology is a powerful tool to fight feed challenges worldwide, as the perspectives of food production need to increase by around 70% by 2050 (Ansari, 2023). It is noteworthy to mention that although agriculture significantly contributes to nutrition, there are impacts on the environment due to the (mis)use of fertilizers and pesticides to achieve higher levels of productivity (Punniyakotti et al., 2024; Srivastav et al., 2024). Thus, nanotechnology can promote better use with high efficiency in plant nutrition and disease control (Kumari et al., 2023; Dos Santos et al., 2024).

Plant disease control is one of the challenges in modern society. Plant diseases significantly affect food security and safety because plant pathogens and pests are responsible for up to 40% yield losses in key crops like maize, rice, and wheat, resulting in global economic losses of about \$220 billion annually. For instance, yield losses are estimated at around 21.5% for wheat, 30.3% for rice, and 22.6% for maize (Wang et al., 2024). Historically, epidemics of plant diseases have exerted considerable influence on societal and political structures. In the contemporary era, new and re-emerging plant diseases persist in presenting substantial challenges, shaping both resource allocation strategies and social responses, including stigmatization and civil unrest. Analyzing specific instances of plant disease epidemics can provide insights into these impacts and their broader implications for society (Ojiambo et al., 2017).

Commercial agriculture predominantly relies on the application of chemical fungicides to mitigate fungal pathogens affecting crop plants by targeting and inhibiting their cellular functions and spores. However, the convenience and low cost associated with these fungicides often lead to their excessive or repeated use. This over application has resulted in detrimental effects on beneficial ecosystems and the environment. Furthermore, the development of resistant fungal strains exacerbates the challenges of managing plant diseases (El-Baky & Amara, 2021). Consequently, there is a significant need for the advancement of non-toxic,

eco-friendly alternative approaches—referred to as green strategies—for fungal control. These alternatives include biological control methods, microbial and botanical fungicides, agricultural nanotechnology, and techniques for fungal cell deactivation and evacuation. These strategies offer promising avenues for effective and sustainable management of plant fungal infections (Porteous-Álvarez et al., 2021).

Metal nanoparticles exert a profound influence on diverse cellular processes in plants. They function as signaling agents that modulate plant responses to environmental stimuli, enhance stress responses, facilitate nutrient uptake, and regulate hormone signaling pathways (Mustafa & Komatsu, 2021). These nanoparticles impact transcriptional processes by interacting with DNA and RNA, thereby altering gene expression and transcript processing (Tumburu et al., 2017). Additionally, metal nanoparticles affect protein synthesis and post-translational modifications, which are crucial for the regulation of hormone signaling and stress responses (Francis et al., 2024; Al-Khayri et al., 2023).

Silver nanoparticles (AgNPs) are extensively employed across multiple industries, including medicine, electronics, water purification, and textiles, due to the antimicrobial and physicochemical properties (Zhang et al., 2016). Global market for AgNPs increased from \$2.20 million (in 2021) to \$2.42 million (in 2022), with an anticipated growth rate of approximately 16% from 2023 to 2028. This growth is largely attributed to advancements in nanotechnology and materials science (Noori et al., 2024). However, the expansion of AgNPs use raises concerns about potential environmental and health impacts, as these nanoparticles can be released into the environment through industrial wastewater, agricultural runoff, and the disposal of consumer products containing AgNPs (Ihtisham et al., 2021).

In this scope, this chapter aims to focus on the peculiarities of AgNPs synthesis and characterization techniques for further applications in the management of fungal pathogens. Moreover, this chapter addresses aspects of antifungal activity and applications reported in the literature for fungal diseases, as well as the challenges and perspectives related to the use of silver nanoparticles (AgNPs). By considering both past and present scenarios, this review aims to illuminate future research directions in the field.

13.2 Synthesis Routes for Silver Nanoparticles

Obtaining silver nanoparticles (AgNPs) can be done through various synthesis routes, with sol-gel, reduction, chemical vapor, and other methods being the most used within the chemical process, laser ablation, microwave, vapor phase in physical and mechanical and bacteria, fungi, plants, and other organic microorganisms, the most used in the green chemistry process (Alaqad & Saleh, 2016).

As shown in Fig. 13.1, a wide range of techniques for obtaining AgNPs can be analyzed within known processes. Thus, the main advantages of each obtaining process will be described, as well as the most used methodologies.

Fig. 13.1 Synthesis routes in chemical, physical and mechanical processes, and green chemistry

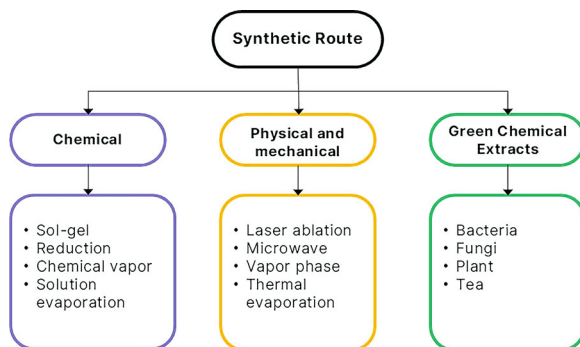


Table 13.1 Relation between AgNPs synthesis and particle size

Method	Size (nm)	References
Reduction	7	Das et al. (2021)
Co-precipitation	43.6	Arland and Kumar (2024)
Sol-gel	1–100	Maharjan et al. (2020)
Chemical vapor	3	Hoyos-Palacio et al. (2019)
Ultrasonic	3.8	Jiang et al. (2024)

13.2.1 Chemical

The chemical process has the advantage of kinetic and thermodynamic control of the synthesis, adjusting its size, shape, and composition, directly reflecting its optical, electronic, and surface properties (Weldegebrieal, 2020; Nikam et al., 2018). In this method, atoms, molecules, or ions in solution form nucleation and then aggregates of these species that finally end up in nanometer-sized regime particles, a process called bottom-up approach (Bachhav & Garde, 2023).

Although some interesting examples are reported in the literature, it is necessary to explore different techniques to analyze the control of size, shape and crystallinity (Jamkhande et al., 2019). Table 13.1 compares methodologies for obtaining AgNPs and the size of the nanoparticles obtained.

With this, it is concluded that the chemical process covers a wide range of sizes and synthesis variations, as long as its reaction parameters are adjusted according to the application of AgNPs.

13.2.2 Physical

The physical method can produce enormous quantities of AgNPs samples in a single process (Osorio-Echavarría et al., 2021), and it is the most suitable method for producing AgNPs powder (Fernández-Benito et al., 2022). The physical route uses external energy and complex equipment to produce AgNPs with nearly narrow size

distribution because nanomaterials are easy to agglomerate due to the lack of stabilizers (Ijaz et al., 2020; Niculescu et al., 2022). To make this technology more popular and economical, it is combined with green synthesis, thus providing more cost advantages, lower energy consumption, and possibly non-agglomeration of synthetic nanoparticles (Yaqoob et al., 2020; Slepíčka et al., 2019; Khan et al., 2019; Harish et al., 2022).

13.2.3 Green Chemical

Green synthesis is the designation of synthesis routes that use low-toxicity, biodegradable, and low-cost chemicals to obtain nanomaterials, having biomolecules or metabolites as the primary source or initiator of the route (Mittal et al., 2013). Green synthesis, biological synthesis, biogenic synthesis, or biosynthesis are terms commonly used for the ecological synthesis of alternative materials. They indicate their versatility, simplicity, and low cost of obtaining these nanomaterials (Ahmed et al., 2022). The main alternative materials used for the synthesis of AgNPs are presented below.

13.2.3.1 Marine Algae

Algae have been highlighted due to their vast bioactive potential, containing compounds such as accessory pigments, proteins, sulfated polysaccharides, and other biomolecules, which act as effective metal reduction and coating agents, providing a robust coating on metal nanoparticles in a single step (Abdel-Raouf et al., 2017, 2019; Algotiml et al., 2022).

When microalgae are exposed to certain concentrations of metals, one of the detoxification strategies is to precipitate the accumulated metal in specific organelles, thus inactivating the potential toxicity of these metals (Davis et al., 2003). Sometimes extracts of micro or macroalgae are also used, in which the metals are easily adsorbed (Gnanadesigan et al., 2012; Roseline et al., 2019).

13.2.3.2 Bacteria

Green chemistry for the synthesis of metal nanoparticles can be implemented using prokaryotic or eukaryotic bacteria or their parts and can occur intra-cellularly or extra-cellularly (Sharma et al., 2008).

The mechanisms involved in the formation of AgNPs are diverse and may involve internalization of specific ions, reduction in the cytoplasmic (or periplasmic, in some cases) environment, or they may also be reduced extra-cellularly, by the action of secreted metabolites or by the action of molecules on the external surface (Pereira et al., 2010; Chuy et al., 2022; Mani et al., 2021a).

AgNPs manufactured from bacterial strains have greater antibacterial activity than metal nanoparticles manufactured by physical and chemical methods, due to the presence of proteins capable of interacting with biomolecules, leading to greater biocompatibility, and may act mainly in the degradation of cells (Mani et al., 2021b; Quinteros et al., 2019; Gecer, 2021; Rajivgandhi et al., 2021).

13.2.3.3 Plants

Plant extracts produce reduced biomolecules, which adhere to the surfaces of nanoparticles to provide stability and protection, resulting in high yields (>70%) and low production costs (Muraro et al., 2023; Rastogi et al., 2017). Furthermore, the synthesis efficiency and properties of AgNPs depend on the nature of the plant (leaf, stem, bark, or seed) and the plant extract (Rani & Shanker, 2019; Gitonga et al., 2023; Mahendran et al., 2021; Prashanth et al., 2021).

Therefore, during synthesis, the extract is usually mixed with a metal salt solution (metal precursor), which is then subjected to biological reduction, followed by nucleation, growth, and stabilization of AgNPs (Pittol et al., 2017; Akhtar et al., 2013; Alam et al., 2014).

13.3 Characterization

The characterization of AgNPs is a primary aspect of nanotechnology. It involves the use of various analytical methods and technologies to understand their properties and behavior (Chaudhari et al., 2020). In general, researchers divide the characterization of synthesized nanoparticles according to their chemical and biological, structural, thermal-optical, or electrical and magnetic properties (Fig. 13.2).

13.3.1 UV-vis Spectroscopy

UV-vis spectroscopy is used to determine the stability and properties of the AgNPs. Factors such as the dielectric medium, nanoparticle size, and chemical context are determinants of the absorption characteristics of AgNPs. The diameter of the nanoparticles is particularly crucial since it defines the frequency at which the resonance of surface plasmons—collective vibrations of electrons present on the surface of metal particles—occurs. Surface plasmon resonance is affected by nanoparticles with sizes between 2 and 100 nanometers, which in turn influences the optical properties of AgNPs. Understanding these relationships is vital to customizing the light absorption of AgNPs for specific applications (Burange et al., 2021).

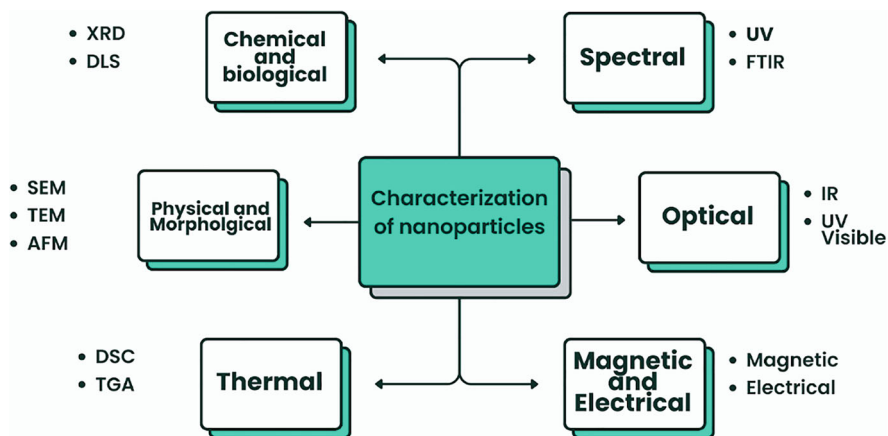


Fig. 13.2 Techniques of the AgNPs characterization

13.3.2 XRD

XRD is a technique used to study the arrangement of atoms within crystals, in other words, this technique measures the degree of crystallinity at the atomic scale. It is an important analysis for determining the crystal structure, lattice parameters, and crystal size. The formation of the diffraction pattern is the key to analysis using this technique (Ali et al., 2023a).

13.3.3 FTIR

FTIR is used to identify the functional group responsible for the AgNPs. This method uses infrared light to characterize the structure of matter at the molecular scale (Naganthran et al., 2022). FTIR is an efficient, economical, and direct method that offers a non-destructive technique to analyze biological molecules in the process of synthesizing silver nanoparticles (Almatroudi, 2020).

13.3.4 DLS

DLS is a non-invasive procedure that measures the hydrodynamic diameter, size, and stability of the AgNPs in solution (Anandalakshmi et al., 2016). This method is widely used due to its rapidity and ability to measure particles ranging from 1 nm to 1 μ m. The technique is based on detecting variations in the intensity of scattered light resulting from the Brownian motion of particles, which is a random movement in

zigzag trajectories. Analysis of this motion reveals that larger particles move more slowly and scatter more light compared to smaller particles, due to their lower mobility.

13.3.5 TEM

TEM is a complementary and very useful technique for the characterization of AgNPs and is used to analyze morphological features (Gowramma et al., 2015). TEM micrographs confirm the size and shape of silver nanoparticles and contribute better spatial resolution compared to scanning electron microscopy (SEM) (Saeed et al., 2020).

13.3.6 AFM

AFM methodology is effective in instantly differentiating the interaction between nanoparticles and lipid bilayers. This technique is particularly valuable for examining the dispersion and agglomeration of silver nanoparticles, as well as their dimensions, morphology, and structural composition. Additionally, it allows nanoscale analysis in aqueous environments, providing a detailed understanding of these processes (Lin et al., 2014).

13.3.7 XPS

XPS is a widely used analytical technique to analyze the surface composition of nanoparticles in liquid forms and determine the per-atom electronic states that include the oxidation stage and electron transfer in the nanoparticles. By determining the elemental composition and chemical bonding, XPS provides valuable insights into the electron transfer mechanisms and properties of nanoparticles in different environmental contexts.

Based on the methods presented, Table 13.2 presents information on the main techniques previously mentioned for different syntheses and applications of nanoparticles.

13.4 Antifungal Activity of Silver Nanoparticles

Given that plant parasites cause at least 25% of output losses globally, synthetic fungicides are the most practical and economical means of managing disease in contemporary agricultural production systems. Because they may be used as novel,

Table 13.2 Characterization, characterization, shape, size, and applications of the AgNPs

Synthesis method	Characterization	Shape and size	Applications	References
Aminolevulinic acid	UV-Visible Spectroscopy; DLS; TEM (EDS).	Spherical; ~30 nm AgNPs and ~12 nm Fe NPs	Agriculture	Franzolin et al. (2022)
Bacteria from soil	UV-Vis spectroscopy and TEM.	5–50 nm	Antimicrobial	Saeed et al. (2020)
<i>Aloe vera</i> and <i>Thuja orientalis</i>	(XRD); (XPS); (FTIR); UV-Vis spectroscopy; TEM; SEM; DLS.	–	Antimicrobial and antifungal activities.	Burange et al. (2021)
PKL	UV VIS; XRD; FTIR; FE-SEM; EDX.	2165 nm	Potential to targeted drug delivery, water treatment, materials for solar cells and biosensors, or electronic devices.	Ali et al. (2023b)
Aqueous extract of fresh garlic	XRD, FE- SEM, AFM, TEM, UV-VIS, Zeta Potential, DLS.	30–350 nm	Sperm treatments	Ali et al. (2023a)
<i>Pedaliium murex</i>	(UV–Vis), (FTIR), (XRD), (FE- SEM), (EDAX), fluorescence emission spectroscopy, (TEM), (DLS), zeta potential and antibacterial activity.	430 nm	Silver-containing antibacterial product	Anandalakshmi et al. (2016)
<i>Eugenia roxburghii</i> DC.	XRD, HR TEM.	19 and 39 nm	Inhibiting biofilm production and bacterial colonies	Giri et al. (2022)

environmentally friendly nano-fungicides with special properties including slowed rates of active component release, improved drug delivery, and increased effectiveness at lower doses, nanoparticles (NPs) are ideal candidates to address this issue. Modern, widely accessible, and extremely efficient fungicides have revolutionized agriculture, particularly with regard to hard-to-control plant diseases. Conventional fungicides have many benefits, but their widespread usage poses a risk to the environment and food safety. As a result, a growing number of fungicide-active ingredients are being phased out in accordance with EU regulations for safety concerns. Farmers are searching for alternatives to NPs in order to get rid of or lessen plant diseases (Malandrakis et al., 2020; Matras et al., 2022).

AgNPs have been demonstrated in researches to have antifungal properties against *A. fumigatus*, *C. globosum*, *M. alpina*, *T. rubrum*, *C. albicans*, *C. tropicalis*, *P. brevicompactum*, and *C. cladosporioides* (Rudramurthy et al., 2016). The production of AgNPs from cow milk was reported by Lee et al. (2013). The decrease of Ag^+ ions, which greatly inhibits the growth of phytopathogens *Colletotrichum coccodes*, *Monilinia* sp., and *Pyricularia* sp., may be attributed to the proteins found in cow milk. Gopinath and Velusamy (2013) concentrated on the extracellular production of silver nanoparticles (AgNPs) utilizing the cell-free culture supernatant of *Bacillus* species GP-23, which showed potent antifungal activity at a concentration of $8 \mu\text{g mL}^{-1}$ against the plant pathogenic fungus *Fusarium oxysporum*. In Mishra et al. (2014), the extracellular synthesis of AgNPs was investigated using the culture supernatant of the agriculturally significant bacterium *Serratia* sp. BHU-S4. The results showed that AgNPs could effectively manage spot blotch disease in wheat, with conidial germination completely inhibited (2, 4, and $10 \mu\text{g mL}^{-1}$); in contrast, conidial germination was 100% in the absence of AgNPs. This suggests the effective use of AgNPs in the management of plant diseases and highlights the intriguing potential of nanofungicides that employ agriculturally significant bacteria.

For many decades, Ag, Ag ions (Ag^+), and Ag compounds have been recognized to possess antibacterial properties. With broad-spectrum antibacterial action against bacteria, fungi, and viruses, silver exhibits an oligodynamic activity. In water and/or bodily fluids, silver and its constituents ionize, and the bioactive silver ions (Ag^+) interact with proteins and amino acids. Ag^+ and Ag compounds have a very harmful effect on microorganisms. Ag^+ also inhibits bacterial and fungal DNA replication and the respiratory chain. Nonetheless, the quantity of biologically active Ag^+ produced and its capacity to interact with the bacterial cell wall strongly correlate with the antibacterial activity of silver and its compounds.

AgNPs are now regarded as a viable substitute for Ag^+ as an antibacterial agent. This is due to the short half-life of Ag^+ 's effects. AgNPs produce ROS which confer enhanced antibacterial characteristics and harm bacteria permanently. They also have a high binding affinity for DNA or RNA, which prevents germs from replicating (Gorczyca et al., 2021). AgNPs also break down DNA, prevent the synthesis of proteins needed to produce ATP, and can produce ROS, which lead to oxidative stress and ultimately stop cell division. AgNPs frequently target a variety of biological organelles, such as the cell membrane's structure, which disrupts electron transport and eventually cellular metabolism, disrupting the energy transfer across the membrane and the electron transport chain, inhibiting the respiratory chain and DNA replication in fungus and bacteria.

In addition, compared to Ag^+ , AgNPs' higher surface-to-volume ratio facilitates easier penetration into cells and enhanced interactions with the cell membrane, which results in the total death of microbial cells. The zeta potential and size of AgNPs affect their antifungal activity. Furthermore, the way in which fungi are inhibited differs depending on the size of the particle. The research that is now accessible demonstrates that the size, surface characteristics, and concentration of AgNPs all play major roles in their biocidal activities. It has been discovered that smaller AgNPs are more harmful than bigger one (Singh et al., 2024).

The strong affinity that silver ions have for phosphate and sulfur groups may account for their antibacterial properties. Ag^+ emitted by NPs interacts with nucleic acids that contain phosphorus and proteins that contain sulfur, mostly on the cell surface. They are known to cause internal ROS generation in cells, which ultimately results in cell death. The primary aspect that appears to be imitating biological activity is the presence of stabilizers adsorbed on the AgNP surface. The controllable electrokinetic characteristics of AgNPs are made possible by the right chemical structure of stabilizing agents. AgNPs stabilized with organic compounds that have protonating and deprotonating groups are usually negatively charged, whereas AgNPs coated with inorganic anions are either positively or negatively charged. Furthermore, AgNPs can more easily pass across biological membranes and accumulate in cell organelles when stabilized by physiologically active substances.

13.5 Antifungal Applications of Silver Nanoparticles on Plant Diseases

AgNPs are widely recognized for their antimicrobial properties, demonstrating efficacy against microorganisms (bacteria and antibiotic-resistant strains) (Kim et al., 2007; Alsalhi et al., 2016). Furthermore, these nanoparticles have also been shown to be effective against fungi, protozoa, and viruses (Stobie et al., 2008; Nawaz et al., 2024).

In the fight against fungal diseases and their harmful effects on agricultural crops, chemical fungicides are the most commonly used products. However, the systematic and excessive application of these synthetic products can promote the development of resistance in pathogens, the scarcity of effective options against specific fungi and possible negative impacts on human health and the environment (Carvalho, 2017).

Thus, AgNPs are currently becoming a promising alternative to chemical pesticides due to their comprehensive antimicrobial properties, which effectively prevent mycelium growth and spore germination in several plant pathogenic fungi (Nowruzi et al., 2024). Thus, being widely investigated as potential antifungal agents for the management of fungal diseases in plants, in Table 13.3 below we can highlight some current works with this approach.

The efficacy of AgNPs derives from their high surface-to-volume ratio, which maximizes interaction with pathogens, as well as their ability to induce oxidative stress in fungal cells (Ingle et al., 2008; Kim et al., 2024). The antimicrobial action mechanism of silver nanoparticles (AgNPs) is initiated by their internalization into cells, which can occur through endocytosis and/or diffusion processes, resulting in the disintegration of the cell membrane (Dakal et al., 2016). Once in the cytoplasm, AgNPs promote the formation of reactive oxygen species (ROS), triggering oxidative stress. This stress activates pro-apoptotic proteins and causes the leakage of cytoplasmic components, consequently, there is significant damage to mitochondria, ribosomes, proteins, enzymes, nucleic acids, and electron transfer systems, leading to cellular apoptosis (Manke et al., 2013).

Table 13.3 Examples of AgNPs biosynthesized as nano-fungicidal agents for plant diseases

AgNPs synthesis method	Size (nm)	Shape	Biological applications	References
Biosynthesized	5–50	Plate	Antifungal activity	Kelkawi et al. (2017)
Biosynthesized	136.9	Spherical	Antifungal activity	Mollick et al. (2015)
Biosynthesized	100	Spherical	Antifungal activity	Shirazi et al. (2022)
Biosynthesized	8–15	Multi shape	Antifungal activity	Mahadevan et al. (2017)
Biosynthesized	4–60	Spherical	Antifungal activity	Rizwana and Alwhibi (2021)
Biosynthesized	25.6	Oval to hexagonal	Antifungal activity	Al-Shmgani et al. (2017)
Biosynthesized	40–50	Spherical	Antifungal activity	Verma and Mehata (2016)
Biosynthesized	35	Spherical, quasi spherical, tri-angular, ellipsoidal	Antifungal activity	Kolya et al. (2015)
Biosynthesized	22	Spherical	Antifungal activity	Verma et al. (2016)
Biosynthesized	12	Spherical	Antifungal activity	Swamy et al. (2015)
Biosynthesized	50.6	Spherical	Antifungal activity	Yugandhar et al. (2015)

AgNPs have demonstrated efficacy in controlling a variety of fungal diseases, ranging from those affecting plant leaves to seed infections, as well as soil-borne pathogens (Mosa et al., 2022; Almaary et al., 2020; Zaki et al., 2022). The diversity in the application forms of AgNPs expands their potential for use, making them valuable tools in combating fungal diseases in plants.

Highlighting the versatility of AgNPs, Baronia et al. (2020) demonstrated that silver nanoparticles have effective nematocidal activity against the rice root-knot nematode (*M. graminicola*). AgNPs were applied as foliar treatment on vegetative growth, yield, and fruit quality of selected trees was investigated, where demonstrated that foliar application of AgNPs brought significant improvements in several metrics: shoot length, total chlorophyll content, percentage of flowers and fruits, fruit yield, and physical and chemical characteristics of the fruits (Mosa et al., 2022).

However, it is essential to consider the potential environmental impacts and safety of AgNPs, as well as the need for further research to optimize their formulations and application methods. Furthermore, the integration of AgNPs into agricultural practices should be carried out in a manner that complements, rather than replaces, other integrated disease management practices. Developing strategies that combine AgNPs with traditional and biological methods may offer a more sustainable and effective approach to fungal disease control, contributing to more resilient and productive agriculture.

13.6 Challenges and Perspectives

One of the main challenges discussed and evaluated was the toxicity risk that AgNP, when released by different products, can present when exposed to the human body, water, soil, and other environmental substances (Syafiuddin et al., 2017). The toxicological studies indicate that the form, the physicochemical properties, the dose, and the level of exposure directly affect this parameter (Tran & Le, 2013; Chawla et al., 2018; Ashique et al., 2022). It is also necessary to explore the relationship between the type of AgNPs and the pH of the food and other storage conditions such as temperature, exposure time and light (Durán et al., 2019; Anandan & Kumar, 2011; Bartłomiejczyk et al., 2013; Marambio-Jones & Hoek, 2010). Better understand human exposure and evaluate the risks of products based on these nanoparticles (Wijnhoven et al., 2009; Kalishwaralal et al., 2010; Raheem et al., 2016).

Given that AgNPs are released into the environment from various commercial products and have toxicity that could harm them, a complete study of their transport behavior is important (Govindaraju et al., 2009). It is necessary to determine the concentration in the environment clearly and qualitatively because it has been demonstrated that the transport of AgNPs depends on environmental conditions and the properties of nanoparticles (Saratale et al., 2018; Vijaykumar et al., 2014). Obtaining AgNPs is also a challenge due to several limitations such as microbiological and reactive components and equipment (Javaid et al., 2017). The main challenges are the morphology (e.g. heterogeneity), polydispersion and instability (Guilger-Casagrande & Lima, 2019; Abdel-Rahim et al., 2017; Balakumaran et al., 2015; Rose et al., 2019).

Nanotechnology has witnessed a renewed interest in methods for manufacturing environmentally friendly nanoparticles (Ahmad et al., 2005), mainly the green synthesis method (Jain et al., 2009; Rupiasih et al., 2015; Phanjom et al., 2012). This ecological approach uses biologically mediated plant extracts as reducing and regenerating agents, providing a sustainable alternative to traditional physical and chemical methods (Sabouri et al., 2022; Nabikhan et al., 2010). This intermediate synthesis in soil eliminates the need for labile chemicals, which results in the production of more stable and biocompatible nanoparticles (Ajitha et al., 2018; Ibrahim, 2015; Hasnain et al., 2019; Oves et al., 2018).

One of the promising applications shown by AgNPs is its outstanding versatility in biological systems (Khatami et al., 2018). It has demonstrated potential in wound healing, cancer treatment, and as vehicles for drug administration (Netala et al., 2018). The ability of Ag nanoparticles to interact with cellular components and biological processes opens possibilities for targeted therapies and greater treatment efficiency (Francis et al., 2018; Goyal et al., 2018). Furthermore, the unique physicochemical properties of AgNPs (e.g. optical, electrical, and thermal properties) contribute to the biological activity (Ajitha et al., 2018; Ramanathan et al., 2018).

These properties can be suitable for biodetection, bioimaging, therapeutic applications, and combination of diagnosis and therapy (Chinnappan et al., 2018). Another important reason to study nanoparticles is their ability to overcome antibiotic resistance (Singh et al., 2010). As a physical agent rather than a chemical one, nanoparticles can be less susceptible to microorganisms developing resistance mechanisms, providing a possible solution to the growing global challenge of drug-resistant bacteria (Shankar et al., 2003). The different properties of platinum nanoparticles are suitable for use in various fields. They are incorporated into medical devices, water filtration systems, textiles, and consumer products (Roy et al., 2014; Sastry et al., 2003).

13.7 Future Remarks

Silver nanoparticles are emerging as a promising tool in agriculture, offering innovative solutions to the diverse challenges in managing fungal diseases affecting plant health. Through extensive research, important insights into their versatility and the fundamental mechanisms at play in agricultural settings have been achieved. In this context, various production methods for silver nanoparticles offer a range of properties that provide diverse antifungal activities for agricultural management. Structural, compositional, and morphological characterization using various techniques advances the understanding of their impact on antifungal efficacy. Consequently, different forms of silver nanoparticles facilitate antifungal actions through the ROS generation and interactions with DNA and RNA.

The use of silver nanoparticles for managing fungal infestations in plants is well-supported by existing literature, which highlights their effectiveness against various fungal strains. However, several challenges persist, including the potential toxicity of these nanoparticles to soil and water and the variability in their size and morphology during synthesis. Despite these issues, green synthesis methods offer an eco-friendly alternative for producing silver nanoparticles, eliminating the need for hazardous chemical reagents. Additionally, the adaptability of silver nanoparticles in overcoming pesticide resistance makes them a valuable tool in addressing fungal infestations. Consequently, there is considerable potential for leveraging silver nanoparticles to enhance fungal management strategies.

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References

- Abdel-Rahim, K., Mahmoud, S. Y., Ali, A. M., Almaary, K. S., Mustafa, A. E. Z. M. A., & Husseiny, S. M. (2017). Extracellular biosynthesis of silver nanoparticles using *Rhizopus stolonifera*. *Saudi Journal of Biological Sciences*, 24, 208–216. <https://doi.org/10.1016/j.sjbs.2016.02.025>
- Abdel-Raouf, N., Al-Enazi, N. M., & Ibraheem, I. B. M. (2017). Green biosynthesis of gold nanoparticles using *Galaxaura elongata* and characterization of their antibacterial activity. *Arabian Journal of Chemistry*, 10, S3029–S3039. <https://doi.org/10.1016/j.arabjc.2013.11.044>
- Abdel-Raouf, N., Al-Enazi, N. M., Ibraheem, I. B. M., Alharbi, R. M., & Alkhulaifi, M. M. (2019). Biosynthesis of silver nanoparticles by using of the marine brown alga *Padina pavonia* and their characterization. *Saudi Journal of Biological Sciences*, 26(6), 1207–1215. <https://doi.org/10.1016/j.sjbs.2018.01.007>
- Ahmad, A., Senapati, S., Khan, M. I., Kumar, R., & Sastry, M. (2005). Extra–/intracellular biosynthesis of gold nanoparticles by an alkalotolerant fungus, *Trichothecium* sp. *Journal of Biomedical Nanotechnology*, 1(1), 47–53. <https://doi.org/10.1166/jbn.2005.012>
- Ahmed, S. F., Mofijur, M., Rafa, N., Chowdhury, A. T., Chowdhury, S., Nahrin, M., & Ong, H. C. (2022). Green approaches in synthesizing nanomaterials for environmental nanobioremediation: Technological advancements, applications, benefits and challenges. *Environmental Research*, 204, 111967–111991. <https://doi.org/10.1016/j.envres.2021.111967>
- Ajitha, B., Reddy, Y. A., Jeon, H. J., & Ahn, C. W. (2018). Synthesis of silver nanoparticles in an eco-friendly way using *Phyllanthus amarus* leaf extract: Antimicrobial and catalytic activity. *Advanced Powder Technology*, 29(1), 86–93. <https://doi.org/10.1016/j.appt.2017.10.015>
- Akhtar, M. S., Panwar, J., & Yun, Y. S. (2013). Biogenic synthesis of metallic nanoparticles by plant extracts. *ACS Sustainable Chemistry & Engineering*, 1, 591–602. <https://doi.org/10.1021/sc300118u>
- Alam, M. A., Subhan, N., Rahman, M. M., Uddin, S. J., Reza, H. M., & Sarker, S. D. (2014). Effect of citrus flavonoids, naringin and naringenin, on metabolic syndrome and their mechanisms of action. *Advances in Nutrition*, 5(4), 404–417. <https://doi.org/10.3945/an.113.005603>
- Alaqad, K., & Saleh, T. A. (2016). Gold and silver nanoparticles: Synthesis methods, characterization routes and applications towards drugs. *Environmental & Analytical Toxicology*, 6, 1–10. <https://doi.org/10.4172/2161-0525.1000384>
- Algotiml, R., Gab-Alla, A., Seoudi, R., Abulreesh, H. H., El-Readi, M. Z., & Elbanna, K. (2022). Anticancer and antimicrobial activity of biosynthesized Red Sea marine algal silver nanoparticles. *Scientific Reports*, 12(1), 2421–2439. <https://doi.org/10.1038/s41598-022-06412-3>
- Ali, I. A. M., Ahmed, A. B., & Al-Ahmed, H. I. (2023a). Green synthesis and characterization of silver nanoparticles for reducing the damage to sperm parameters in diabetic compared to metformin. *Scientific Reports*, 13(1), 2256–2270. <https://doi.org/10.1038/s41598-023-29412-3>
- Ali, M. H., Azad, M. A. K., Khan, K. A., Rahman, M. O., Chakma, U., & Kumer, A. (2023b). Analysis of crystallographic structures and properties of silver nanoparticles synthesized using PKL extract and nanoscale characterization techniques. *ACS Omega*, 8(31), 28133–28142. <https://doi.org/10.1021/acsomega.3c01261>
- Al-Khayri, J. M., Rashmi, R., Ulhas, R. S., Sudheer, W. N., Banadka, A., Nagella, P., Aldaej, M. I., Rezk, A. A. S., Shehata, W. F., & Almaghasla, M. I. (2023). The role of nanoparticles in response of plants to abiotic stress at physiological, biochemical, and molecular levels. *Plants*, 12, 292–317. <https://doi.org/10.3390/plants12020292>
- Almaary, K. S., Sayed, S. R. M., Abd-Elkader, O. H., Dawoud, T. M., Orabi, N. F. E., & Elgorban, A. M. (2020). Complete green synthesis of silver-nanoparticles applying seed-borne *Penicillium duclauxii*. *Saudi Journal of Biological Sciences*, 27(5), 1333–1339. <https://doi.org/10.1016/j.sjbs.2019.12.022>
- Almatroudi, A. (2020). Silver nanoparticles: Synthesis, characterization and biomedical applications. *Open Life Sciences*, 15(1), 819–839. <https://doi.org/10.1515/biol-2020-0094>

- Alsalthi, M. S., Devanesan, S., Alfuraydi, A. A., Vishnubalaji, R., Munusamy, M. A., Murugan, K., Nicoletti, M., & Benelli, G. (2016). Green synthesis of silver nanoparticles using *Pimpinella anisum* seeds: Antimicrobial activity and cytotoxicity on human neonatal skin stromal cells and colon cancer cells. *International Journal of Nanomedicine*, 11, 4439–4449. <https://doi.org/10.2147/ijn.s113193>
- Al-Shmangani, H. S., Mohammed, W. H., Sulaiman, G. M., & Saadoon, A. H. (2017). Biosynthesis of silver nanoparticles from *Catharanthus roseus* leaf extract and assessing their antioxidant, antimicrobial, and wound-healing activities. *Artificial Cells, Nanomedicine, and Biotechnology*, 45, 1234–1240. <https://doi.org/10.1080/21691401.2016.1220950>
- Anandalakshmi, K., Venugobal, J., & Ramasamy, V. J. A. N. (2016). Characterization of silver nanoparticles by green synthesis method using *Pedaliu murex* leaf extract and their antibacterial activity. *Applied Nanoscience*, 6, 399–408. <https://doi.org/10.1007/s13204-015-0449-z>
- Anandan, A., & Kumar, A. (2011). Exposures to TiO₂ and Ag nanoparticles: What are human health risks. *Science & Society*, 9(2), 155–162.
- Ansari, M. A. (2023). Nanotechnology in food and plant science: Challenges and future prospects. *Plants*, 12, 2565–2599. <https://doi.org/10.3390/plants12132565>
- Arland, S. E., & Kumar, J. (2024). Green and chemical syntheses of silver nanoparticles: Comparative and comprehensive study on characterization, therapeutic potential, and cytotoxicity. *European Journal of Medicinal Chemistry Reports*, 11, 1–13. <https://doi.org/10.1016/j.ejmc.2024.100168>
- Ashique, S., Upadhyay, A., Hussain, A., Bag, S., Chatterjee, D., Rihan, M., & Dua, K. (2022). Green biogenic silver nanoparticles, therapeutic uses, recent advances, risk assessment, challenges, and future perspectives. *Journal of Drug Delivery Science and Technology*, 77, 103876–103895. <https://doi.org/10.1016/j.jddst.2022.103876>
- Bachhav, K., & Garde, A. S. (2023). Versatile synthesis of zinc oxide nanoparticles via chemical route: A review. *Materials Today: Proceedings*, 2023, 1–9. <https://doi.org/10.1016/j.matpr.2023.08.269>
- Balakumaran, M. D., Ramachandran, R., & Kalaicheilvan, P. T. (2015). Exploitation of endophytic fungus, *Guignardia mangiferae* for extracellular synthesis of silver nanoparticles and their *in vitro* biological activities. *Microbiological Research*, 178, 9–17. <https://doi.org/10.1016/j.micres.2015.05.009>
- Baronia, R., Kumar, P., Singh, S. P., & Walia, R. K. (2020). Silver nanoparticles as a potential nematicide against *Meloidogyne graminicola*. *Journal of Nematology*, 52, 1–9. <https://doi.org/10.21307/jofnem-2020-002>
- Bartłomiejczyk, T., Lankoff, A., Kruszewski, M., & Szumiel, I. (2013). Silver nanoparticles—allies or adversaries? *Annals of Agricultural and Environmental Medicine*, 20(1), 48–54.
- Brandelli, A. (2020). The interaction of nanostructured antimicrobials with biological systems: Cellular uptake, trafficking and potential toxicity. *Food Science and Human Wellnes*, 9, 8–20. <https://doi.org/10.1016/j.fshw.2019.12.003>
- Burange, P. J., Tawar, M. G., Bairagi, R. A., Malviya, V. R., Sahu, V. K., Shewatkar, S. N., & Mamurkar, R. R. (2021). Synthesis of silver nanoparticles by using *Aloe vera* and *Thuja orientalis* leaves extract and their biological activity: A comprehensive review. *Bulletin of the National Research Centre*, 45, 181–193. <https://doi.org/10.1186/s42269-021-00639-2>
- Carvalho, F. P. (2017). Pesticides, environment, and food safety. *Food and Energy Security*, 6(2017), 48–60. <https://doi.org/10.1002/fes3.108>
- Chaudhari, A. V., Deokate, U. A., & Salvi, U. B. (2020). Review on synthesis, characterization and applications of silver nanoparticles. *International Journal of Creative Research Thoughts*, 8(5), 2320–2882.
- Chawla, J., Singh, D., Sundaram, B., & Kumar, A. (2018). Identifying challenges in assessing risks of exposures of silver nanoparticles. *Exposure and Health*, 10, 61–75. <https://doi.org/10.1007/s12403-017-0245-y>

- Chinnappan, S., Kandasamy, S., Arumugam, S., Seralathan, K. K., Thangaswamy, S., & Muthusamy, G. (2018). Biomimetic synthesis of silver nanoparticles using flower extract of *Bauhinia purpurea* and its antibacterial activity against clinical pathogens. *Environmental Science and Pollution Research*, 25, 963–969. <https://doi.org/10.1007/s11356-017-0841-1>
- Chuy, G. P., Muraro, P. C. L., Viana, A. R., Pavoski, G., Espinosa, D. C. R., Vizzotto, B. S., & Da Silva, W. L. (2022). Green nanoarchitectonics of silver nanoparticles for antimicrobial activity against resistant pathogens. *Journal of Inorganic and Organometallic Polymers and Materials*, 32, 1213–1222. <https://doi.org/10.1007/s10904-021-02162-3>
- Dakal, T. C., Kumar, A., Majumdar, R. S., & Yadav, V. (2016). Mechanistic basis of antimicrobial actions of silver nanoparticles. *Frontiers in Microbiology*, 7, 1831–1847. <https://doi.org/10.3389/fmicb.2016.01831>
- Das, S., Bandyopadhyay, K., & Gosh, M. M. (2021). Effect of stabilizer concentration on the size of silver nanoparticles synthesized through chemical route. *Inorganic Chemistry Communications*, 123, 1–6. <https://doi.org/10.1016/j.inoche.2020.108319>
- Davis, T. A., Volesky, B., & Mucci, A. (2003). A review of the biochemistry of heavy metal biosorption by brown algae. *Water Research*, 37(18), 4311–4330. [https://doi.org/10.1016/S0043-1354\(03\)00293-8](https://doi.org/10.1016/S0043-1354(03)00293-8)
- Dos Santos, O. A. L., Dos Santos, M. S., Antunes Filho, S., & Backx, B. P. (2024). Nanotechnology for the control of plant pathogens and pests. *Plant Nano Biology*, 8, 100080–100093. <https://doi.org/10.1016/j.plana.2024.100080>
- Durán, N., Rolim, W. R., Durán, M., Fávoro, W. J., & Seabra, A. B. (2019). Nanotoxicology of silver nanoparticles: Toxicity in animals and humans. *Química Nova*, 42(2), 206–213. <https://doi.org/10.21577/0100-4042.20170318>
- El-Baky, N. A., & Amara, A. A. F. (2021). Recent approaches towards control of fungal diseases in plants: An updated review. *Journal of Fungi*, 7, 900–916. <https://doi.org/10.3390/jof7110900>
- Fernández-Benito, A., Hoyos, M., López-Manchado, M. A., & Sørensen, T. J. (2022). A physical Unclonable function based on recyclable polymer nanoparticles to enable the circular economy. *ACS Applied Nano Materials*, 5(10), 13752–13760. <https://doi.org/10.1021/acsanm.2c00808>
- Francis, S., Joseph, S., Koshy, E. P., & Mathew, B. (2018). Microwave assisted green synthesis of silver nanoparticles using leaf extract of *elephantopus scaber* and its environmental and biological applications. *Artificial Cells, Nanomedicine, and Biotechnology*, 46, 795–804. <https://doi.org/10.1080/21691401.2017.1345921>
- Francis, D. V., Abdalla, A. K., Mahakham, W., Sarmah, A. K., & Ahmed, Z. F. R. (2024). Interaction of plants and metal nanoparticles: Exploring its molecular mechanisms for sustainable agriculture and crop improvement. *Environment International*, 190, 108859–108876. <https://doi.org/10.1016/j.envint.2024.108859>
- Franzolin, M. R., Lopes, I. S., Courrol, D. S., Barreto, S. S., & Courrol, L. C. (2022). Synthesis, characterization, antimicrobial activity, and toxicity evaluation of aminolevulinic acid–silver and silver–iron nanoparticles for potential applications in agriculture. *RSC Advances*, 12(46), 30094–30103. <https://doi.org/10.1039/d2ra05135d>
- Gecer, E. N. (2021). Green synthesis of silver nanoparticles from *Salvia aethiopis* L. and their antioxidant activity. *Journal of Inorganic and Organometallic Polymers and Materials*, 31, 4402–4409. <https://doi.org/10.1007/s10904-021-02057-3>
- Giri, A. K., Jena, B., Biswal, B., Pradhan, A. K., Arakha, M., Acharya, S., & Acharya, L. (2022). Green synthesis and characterization of silver nanoparticles using *Eugenia roxburghii* DC. extract and activity against biofilm-producing bacteria. *Scientific Reports*, 12(1), 8383–8391. <https://doi.org/10.1038/s41598-022-12484-y>
- Gitonga, D., Singh, P. R., & Hajihassani, A. (2023). Detection of guava root-knot nematode, *Meloidogyne enterolobii* infecting *Psidium guajava* orchards in Homestead, Florida. *Australasian Plant Disease Notes*, 18(1), 20–24. <https://doi.org/10.1007/s13314-023-00506-1>
- Gnanadesigan, M., Anand, M., Ravikumar, S., Maruthupandy, M., Syed Ali, M., Vijayakumar, V., & Kumaraguru, A. K. (2012). Antibacterial potential of biosynthesised silver nanoparticles using *Avicennia marina* mangrove plant. *Applied Nanoscience*, 2, 143–147. <https://doi.org/10.1007/s13204-011-0048-6>

- Gopinath, V., & Velusamy, P. (2013). Extracellular biosynthesis of silver nanoparticles using *Bacillus* sp. GP-23 and evaluation of their antifungal activity towards *Fusarium oxysporum*. *Spectrochimica Acta Part A Molecular and Biomolecular Spectroscopy*, 106, 170–174. <https://doi.org/10.1016/j.saa.2012.12.087>
- Gorczyca, A., Pocięcha, E., & Matras, E. (2021). Nanotechnology in agriculture, the food sector, and remediation: Prospects, relations, and constraints. In R. Prasad (Ed.), *Environmental pollution and remediation* (pp. 1–34). Springer Singapore.
- Govindaraju, K., Kiruthiga, V., Kumar, V. G., & Singaravelu, G. (2009). Extracellular synthesis of silver nanoparticles by a marine alga, *Sargassum wightii* Grevilli and their antibacterial effects. *Journal of Nanoscience and Nanotechnology*, 9(9), 5497–5501. <https://doi.org/10.1166/jnn.2009.1199>
- Gowramma, B., Keerthi, U., Rafi, M., & Rao, D. M. (2015). Biogenic silver nanoparticles production and characterization from native strain of *Corynebacterium* species and its antimicrobial activity. *3 Biotech*, 5, 195–201. <https://doi.org/10.1007/s13205-014-0210-4>
- Goyal, S., Gupta, N., Kumar, A., Chatterjee, S., & Nimesh, S. (2018). Antibacterial, anticancer and antioxidant potential of silver nanoparticles engineered using *Trigonella foenum-graecum* seed extract. *IET Nanobiotechnology*, 12, 526–533. <https://doi.org/10.1049/iet-nbt.2017.0089>
- Guilger-Casagrande, M., & Lima, R. D. (2019). Synthesis of silver nanoparticles mediated by fungi: A review. *Frontiers in Bioengineering and Biotechnology*, 7, 287–302. <https://doi.org/10.3389/fbioe.2019.00287>
- Harish, V., Ansari, M. M., Tewari, D., Gaur, M., Yadav, A. B., García-Betancourt, M. L., & Barhoum, A. (2022). Nanoparticle and nanostructure synthesis and controlled growth methods. *Nanomaterials (Basel)*, 12(18), 3226–3256. <https://doi.org/10.3390/nano12183226>
- Hasnain, M. S., Javed, M. N., Alam, M. S., Rishishwar, P., Rishishwar, S., & Ali, S. (2019). Purple heart plant leaves extract-mediated silver nanoparticle synthesis: Optimization by Box-Behnken design. *Materials Science & Engineering C, Materials for Biological Applications*, 99, 1105–1114. <https://doi.org/10.1016/j.msec.2019.02.061>
- Hoyos-Palacio, L. M., Castro, D. P. C., Ortiz-Trujillo, I. C., Palacio, L. E. B., Upegui, B. J. G., Mora, N. J. E., & Cornelio, J. A. C. (2019). Compounds of carbon nanotubes decorated with silver nanoparticles via *in-situ* by chemical vapor deposition (CVD). *Journal of Materials Research and Technology*, 8(6), 5893–5898. <https://doi.org/10.1016/j.jmrt.2019.09.062>
- Ibrahim, H. M. (2015). Green synthesis and characterization of silver nanoparticles using banana peel extract and their antimicrobial activity against representative microorganisms. *Journal of Radiation Research and Applied Sciences*, 8, 265–275. <https://doi.org/10.1016/j.jrras.2015.01.007>
- Ihtisham, M., Noori, A., Yadav, S., Sarraf, M., Kumari, P., Brestic, M., Imran, M., Jiang, F., Yan, X., & Rastogi, A. (2021). Silver nanoparticle's toxicological effects and phytoremediation. *Nanomaterials (Basel)*, 11, 2164–2181. <https://doi.org/10.3390/nano11092164>
- Ijaz, I., Gilani, E., Nazir, A., & Bukhari, A. (2020). Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles. *Green Chemistry Letters and Reviews*, 13(3), 223–245. <https://doi.org/10.1080/17518253.2020.1802517>
- Ingle, A., Gade, A., Pierrat, S., Sonnichsen, C., & Rai, M. (2008). Mycosynthesis of silver nanoparticles using the fungus *Fusarium acuminatum* and its activity against some human pathogenic bacteria. *Current Nanoscience*, 4, 141–144. <https://doi.org/10.2174/157341308784340804>
- Jain, D., Daima, H. K., Kachhwaha, S., & Kothari, S. L. (2009). Synthesis of plant-mediated silver nanoparticles using papaya fruit extract and evaluation of their antimicrobial activities. *Digest Journal of Nanomaterials and Biostructures*, 4(3), 557–563.
- Jamkhande, P. G., Ghule, N. W., Bamer, A. H., & Kalaskar, M. G. (2019). Metal nanoparticles synthesis: An overview on methods of preparation, advantages and disadvantages, and applications. *Journal of Drug Delivery Science and Technology*, 53, 101174–101185. <https://doi.org/10.1016/j.jddst.2019.101174>

- Javaid, A., Oloketuyi, S. F., Khan, M. M., & Khan, F. (2017). Diversity of bacterial synthesis of silver nanoparticles. *BioNanoScience*, 8(1), 43–59. <https://doi.org/10.1007/s12668-017-0496-x>
- Jiang, W., Zhang, Y., Yang, D., Qiu, X., & Li, Z. (2024). Ultrasonic-assisted synthesis of lignin-based ultrasmall silver nanoparticles for photothermal-mediated sterilization. *International Journal of Biological Macromolecules*, 262(1), 1–9. <https://doi.org/10.1016/j.ijbiomac.2024.129827>
- Kalishwaralal, K., BarathManiKanth, S., Pandian, S. R., Deepak, V., & Gurunathan, S. (2010). Silver nanoparticles impede the biofilm formation by *Pseudomonas aeruginosa* and *Staphylococcus epidermidis*. *Colloids and Surfaces B: Biointerfaces*, 79(2), 340–344. <https://doi.org/10.1016/j.colsurfb.2010.04.014>
- Kelkawi, A. H. A., Kajani, A. A., & Bordbar, A. K. (2017). Green synthesis of silver nanoparticles using *Mentha pulegium* and investigation of their antibacterial, antifungal and anticancer activity. *IET Nanobiotechnology*, 11, 370–376. <https://doi.org/10.1049/iet-nbt.2016.0103>
- Khan, I., Saeed, K., & Khan, I. (2019). Nanoparticles: Properties, applications and toxicities. *Arabian Journal of Chemistry*, 12(7), 908–931. <https://doi.org/10.1016/j.arabjc.2017.05.011>
- Khatami, M., Sharifi, I., Nobre, M. A., Zafarnia, N., & Aflatoonian, M. R. (2018). Waste-grass-mediated green synthesis of silver nanoparticles and evaluation of their anticancer, antifungal and antibacterial activity. *Green Chemistry Letters and Reviews*, 11, 125–134. <https://doi.org/10.1080/17518253.2018.1444797>
- Kim, J. S., Kuk, E., Yu, K. N., Kim, J. H., Park, S. J., Lee, H. J., Kim, S. H., Park, Y. H., Hwang, C. Y., Kim, Y. K., Lee, Y. S., Jeong, D. H., & Cho, M. H. (2007). Antimicrobial effects of silver nanoparticles. *Nanomedicine*, 3(1), 95–101. <https://doi.org/10.1016/j.nano.2006.12.001>
- Kim, D., Patel, S., Rasool, K., Lone, N., Bhatia, S., Seth, C., & Ghodake, G. (2024). Bioinspired silver nanoparticle-based nanocomposites for effective control of plant pathogens: A review. *Science of the Total Environment*, 908, 168318. <https://doi.org/10.1016/j.scitotenv.2023.168318>
- Kolya, H., Maiti, P., Pandey, A., & Tripathy, T. (2015). Green synthesis of silver nanoparticles with antimicrobial and azo dye (Congo red) degradation properties using *Amaranthus gangeticus* Linn leaf extract. *Journal of Analytical Science and Technology*, 6, 33–39. <https://doi.org/10.1186/s40543-015-0074-1>
- Kumari, A., Rana, V., Yadav, S. K., & Kumar, V. (2023). Nanotechnology as a powerful tool in plant sciences: Recent developments, challenges and perspectives. *Plant Nano Biology*, 5, 100046–100055. <https://doi.org/10.1016/j.plana.2023.100046>
- Lee, K. J., Park, S. H., Govarthan, M., Hwang, P. H., Seo, Y. S., Cho, M., Lee, W. H., Lee, J. Y., Kamala-Kannan, S., & Oh, B. (2013). Synthesis of silver nanoparticles using cow milk and their antifungal activity against phytopathogen. *Materials Letters*, 105, 128–131. <https://doi.org/10.1016/j.matlet.2013.04.076>
- Lin, L. C., Lin, S., Wang, P. C., & Sridhar, R. (2014). Techniques for physicochemical characterization of nanomaterials. *Biotechnology Advances*, 32(4), 711–726. <https://doi.org/10.1016/j.biotechadv.2013.11.006>
- Mahadevan, S., Vijayakumar, S., & Arulmozhi, P. (2017). Green synthesis of silver nano particles from *Atalantia monophylla* (L) Correa leaf extract, their antimicrobial activity and sensing capability of H₂O₂. *Microbial Pathogenesis*, 113, 445–450. <https://doi.org/10.1016/j.micpath.2017.11.029>
- Maharjan, S., Liao, K., Wang, A. J., Zhu, Z., McElhenny, B. P., Bao, J., & Curran, S. A. (2020). Sol-gel synthesis of stabilized silver nanoparticles in an organosiloxane matrix and its optical nonlinearity. *Chemical Physics*, 532, 1–7. <https://doi.org/10.1016/j.chemphys.2019.110610>
- Mahendran, D., Kavi Kishor, P. B., Geetha, N., Manish, T., Sahi, S. V., & Venkatachalam, P. (2021). Efficient antibacterial/biofilm, anti-cancer and photocatalytic potential of titanium dioxide nanocatalysts green synthesised using *Gloriosa superba* rhizome extract. *Journal of Experimental Nanoscience*, 16, 11–30. <https://doi.org/10.1080/17458080.2021.1872781>

- Malandrakis, A. A., Kavroulakis, N., & Chrysikopoulos, C. V. (2020). Synergy between Cu-NPs and fungicides against *Botrytis cinerea*. *Science of the Total Environment*, 703, 135557. <https://doi.org/10.1016/j.scitotenv.2019.135557>
- Mani, M., Harikrishnan, R., Purushothaman, P., Pavithra, S., Rajkumar, P., Kumaresan, S., Al-Farraj, D. A., Elshikh, M. S., Balasubramanian, B., & Kaviyarasu, K. (2021a). Systematic green synthesis of silver oxide nanoparticles for antimicrobial activity. *Environmental Science Journals*, 202, 11627–111635. <https://doi.org/10.1016/j.envres.2021.111627>
- Mani, M., Okla, M. K., Selvaraj, S., Kumar, A. R., Kumaresan, S., Muthukumaran, A., Kaviyarasu, K., El-Tayeb, M. A., Elbadawi, Y. B., Almaary, K. S., Almunqedhi, B. M. A., & Elshikh, M. S. (2021b). A novel biogenic *Allium cepa* leaf mediated silver nanoparticles for antimicrobial, antioxidant, and anticancer effects on MCF-7 cell line. *Environmental Science Journals*, 198, 111199–111207. <https://doi.org/10.1016/j.envres.2021.111199>
- Manke, A., Wang, L., & Rojanasakul, Y. (2013). Mechanisms of nanoparticle-induced oxidative stress and toxicity. *BioMed Research International*, 2013, 1–15. <https://doi.org/10.1155/2013/942916>
- Marambio-Jones, C., & Hoek, E. M. V. A. (2010). Review of the antibacterial effects of silver nanomaterials and potential implications for human health and environment. *Journal of Nanoparticle Research*, 12(5), 1531–1551. <https://doi.org/10.1007/s11051-010-9900-y>
- Matras, E., Gorczyca, A., Przemieniecki, S. W., & Oćwieja, M. (2022). Surface properties-dependent antifungal activity of silver nanoparticles. *Scientific Reports*, 12(1), 18046–18062. <https://doi.org/10.1038/s41598-022-22659-2>
- Mishra, S., Singh, B. R., Singh, A., Keswani, C., Naqvi, A. H., & Singh, H. B. (2014). Biofabricated silver nanoparticles act as a strong fungicide against *Bipolaris sorokiniana* causing spot blotch disease in wheat. *PLoS One*, 9(5), e97881. <https://doi.org/10.1371/journal.pone.0097881>
- Mittal, A. K., Chisti, Y., & Banerjee, U. C. (2013). Synthesis of metallic nanoparticles using plant extracts. *Biotechnology Advances*, 31, 346–356. <https://doi.org/10.1016/j.biotechadv.2013.01.003>
- Mollick, M. M. R., Rana, D., Dash, S. K., Chattopadhyay, S., Bhowmick, B., Maity, D., Mondal, D., Pattanayak, S., Roy, S., Chakraborty, M., & Chattopadhyay, D. (2015). Studies on green synthesized silver nanoparticles using *Abelmoschus esculentus* (L.) pulp extract having anti-cancer (*in vitro*) and antimicrobial applications. *Arabian Journal of Chemistry*, 3, 2572–2584. <https://doi.org/10.1016/j.arabjc.2015.04.033>
- Mosa, W. F. A., Mackled, M. I., Abdelsalam, N. R., Behiry, S. I., Al-Askar, A. A., Basile, A., Abdelkhalek, A., Elsharkawy, M. M., & Salem, M. Z. M. (2022). Impact of silver nanoparticles on lemon growth performance: Insecticidal and antifungal activities of essential oils from peels and leaves. *Frontiers in Plant Science*, 13, 898846–898860. <https://doi.org/10.3389/fpls.2022.898846>
- Muraro, P. C. L., Pavoski, G., Espinosa, D. C. R., Ruiz, Y. P. M., Galembeck, A., & Da Silva, W. L. (2023). Ag/TiNPs nanocatalyst: Biosynthesis, characterization and photocatalytic activity. *Journal of Photochemistry and Photobiology, A: Chemistry*, 439, 114598–114604. <https://doi.org/10.1016/j.jphotochem.2023.114598>
- Mustafa, G., & Komatsu, S. (2021). Plant proteomic research for improvement of food crops under stresses: A review. *Molecular Omics*, 17, 860–880. <https://doi.org/10.1039/d1mo00151e>
- Nabikhan, A., Kandasamy, K., Raj, A., & Alikunhi, N. M. (2010). Synthesis of antimicrobial silver nanoparticles by callus and leaf extracts from saltmarsh plant, *Sesuvium portulacastrum* L. *Colloids and Surfaces B: Biointerfaces*, 79, 488–493. <https://doi.org/10.1016/j.colsurfb.2010.05.018>
- Naganthran, A., Verasoundarapandian, G., Khalid, F. E., Masarudin, M. J., Zulkharnain, A., Nawawi, N. M., & Ahmad, S. A. (2022). Synthesis, characterization and biomedical application of silver nanoparticles. *Materials*, 15(2), 427–469. <https://doi.org/10.3390/ma15020427>
- Nawaz, A. H., Mehmood, A., Khalid, A. U. R., Khan, M. A. R., Khan, G., Ahmad, K. S., & Nabi, A. G. (2024). Green synthesis of silver nanoparticles for their antifungal activity against

- anthracnose disease causing *Colletotrichum capsica*. *Biocatalysis and Agricultural Biotechnology*, 58, 103178. <https://doi.org/10.1016/j.bcab.2024.103178>
- Netala, V. R., Bukke, S., Domdi, L., Soneya, S. G., Reddy, S., & Bethu, M. S. (2018). Biogenesis of silver nanoparticles using leaf extract of *Indigofera hirsuta* L. and their potential biomedical applications (3-in-1 system). *Artificial Cells, Nanomedicine, and Biotechnology*, 46, 1138–1148. <https://doi.org/10.1080/21691401.2018.1446967>
- Niculescu, A. G., Chircov, C., & Grumezescu, A. M. (2022). Magnetite nanoparticles: Synthesis methods—a comparative review. *Methods*, 199, 16–27. <https://doi.org/10.1016/j.ymeth.2021.04.018>
- Nikam, A. V., Prasad, B. L. V., & Kulkarni, A. A. (2018). Wet chemical synthesis of metal oxide nanoparticles: A review. *CrystEngComm*, 20, 5091–5107. <https://doi.org/10.1039/c8ce00487k>
- Noori, A., Hasanuzzaman, M., Roychowdhury, R., Sarraf, M., Afzal, S., Das, S., & Rastogi, A. (2024). Silver nanoparticles in plant health: Physiological response to phytotoxicity and oxidative stress. *Plant Physiology and Biochemistry*, 209, 108538–108548. <https://doi.org/10.1016/j.plaphy.2024.108538>
- Nowruzi, B., Majidi, M., & Darvishi, R. (2024). Antifungal screening of silver nanoparticles biosynthesized by *Aliinostoc oryzae* against plant pathogenic fungi. *South African Journal of Botany*, 171, 473–484. <https://doi.org/10.1016/j.sajb.2024.06.023>
- Ojiambo, P. S., Yuen, J., Van Der Bosch, F., & Maden, L. V. (2017). Epidemiology: Past, present, and future impacts on understanding disease dynamics and improving plant disease management—A summary of focus issue articles. *Phytopathology*, 107, 1092–1094. <https://doi.org/10.1094/phyto-07-17-0248-fi>
- Osorio-Echavarría, J., Osorio-Echavarría, J., Ossa-Orozco, C. P., & Gómez-Vanegas, N. A. (2021). Synthesis of silver nanoparticles using white-rot fungus *Anamorphous Bjerkandera* sp. R1: Influence of silver nitrate concentration and fungus growth time. *Scientific Reports*, 11(1), 3842–3856. <https://doi.org/10.1038/s41598-021-82514-8>
- Oves, M., Aslam, M., Rauf, M. A., Qayyum, S., Qari, H. A., & Khan, M. S. (2018). Antimicrobial and anticancer activities of silver nanoparticles synthesized from the root hair extract of *Phoenix dactylifera*. *Materials Science & Engineering C, Materials for Biological Applications*, 89, 429–443. <https://doi.org/10.1016/j.msec.2018.03.035>
- Pereira, V. J., Fernandes, D., Carvalho, G., Benoliel, M. J., San Romão, M. V., & Crespo, M. B. (2010). Assessment of the presence and dynamics of fungi in drinking water sources using cultural and molecular methods. *Water Resources*, 44, 4850–4859. <https://doi.org/10.1016/j.watres.2010.07.018>
- Phanjom, P., Sultana, A., Sarma, H., Ramchiary, J., Goswami, K., & Baishya, P. (2012). Plant-mediated synthesis of silver nanoparticles using *Elaeagnus latifolia* leaf extract. *Digest Journal of Nanomaterials and Biostructures*, 7(3), 1117–1123.
- Pittol, M., Aslameski, D., Simões, D. N., Ribeiro, V. F., & Santana, R. M. C. (2017). Macroscopic effects of silver nanoparticles and titanium dioxide on edible plant growth. *Environmental Nanotechnology, Monitoring & Management*, 8, 127–133. <https://doi.org/10.1016/j.enmm.2017.07.003>
- Porteous-Álvarez, A. J., Maldonado-González, M. M., Mayo-Prieto, S., Lorenzana, A., Paniagua-García, A. I., & Casquero, P. A. (2021). Green strategies of powdery Mildew control in Hop: From organic products to nanoscale carriers. *Journal of Fungi*, 7, 490–500. <https://doi.org/10.3390/jof7060490>
- Prashanth, V., Priyanka, K., & Remya, N. (2021). Solar photocatalytic degradation of metformin by TiO₂ synthesized using *Calotropis gigantea* leaf extract. *Water Science and Technology*, 83, 1072–1084. <https://doi.org/10.2166/wst.2021.040>
- Punniyakotti, P., Vinayagam, S., Rajamohan, R., Priya, S. D., Moovendhan, M., & Sundaram, T. (2024). Environmental fate and ecotoxicological behaviour of pesticides and insecticides in non-target environments: Nanotechnology-based mitigation strategies. *Journal of Environmental Chemical Engineering*, 12, 113349–113363. <https://doi.org/10.1016/j.jece.2024.113349>
- Quinteros, M. A., Bonilla, J. O., Alborés, S. V., Villegas, L. B., & Páez, P. L. (2019). Biogenic nanoparticles: Synthesis, stability and biocompatibility mediated by proteins of *Pseudomonas*

- aeruginosa*. *Colloids and Surfaces B: Biointerfaces*, 184, 110517–110522. <https://doi.org/10.1016/j.colsurfb.2019.110517>
- Raheem, H. Q., Al-Thahab, A. A., & Abd, F. G. (2016). Different methods for detection silver nanoparticles produced by proteus mirabilis bacteria. *International Journal of PharmTech Research*, 9(4), 368–376.
- Rajivgandhi, G. N., Kanisha, C. C., Vijayakumar, S., Alharbi, N. S., Kadaikunnan, S., Khaled, J. M., Alanzi, K. F., & Li, W. J. (2021). Enhanced anti-biofilm activity of facile synthesized silver oxide nanoparticles against *K. pneumoniae*. *Journal of Inorganic and Organometallic Polymers*, 31, 3921–3933. <https://doi.org/10.1007/s10904-021-02013-1>
- Ramanathan, S., Gopinath, S. C., Anbu, P., Lakshmipriya, T., Kasim, F. H., & Lee, C. G. (2018). Eco-friendly synthesis of *Solanum trilobatum* extract-capped silver nanoparticles is compatible with good antimicrobial activities. *Journal of Molecular Structure*, 1160, 80–91. <https://doi.org/10.1016/j.molstruc.2018.01.056>
- Rani, M., & Shanker, U. (2019). Insight in to the degradation of bisphenol A by doped ZnO@ZnHCF nanocubes: High photocatalytic performance. *Journal of Colloid and Interface Science*, 530, 16–28. <https://doi.org/10.1016/j.jcis.2018.06.070>
- Rastogi, M., Sytar, O., Kalaji, H. M., He, X., Mbarki, S., & Brestic, M. (2017). Impact of metal and metal oxide nanoparticles on plant: A critical review. *Frontiers in Chemistry*, 5, 78–93. <https://doi.org/10.3389/fchem.2017.00078>
- Rizwana, H., & Alwhibi, M. S. (2021). Biosynthesis of silver nanoparticles using leaves of *Mentha pulegium*, their characterization, and antifungal properties. *Green Processing and Synthesis*, 10, 824–834. <https://doi.org/10.1515/gps-2021-0079>
- Rose, G. K., Soni, R., Rishi, P., & Soni, S. K. (2019). Optimization of the biological synthesis of silver nanoparticles using *Penicillium oxalicum* GRS-1 and their antimicrobial effects against common food-borne pathogens. *Green Processing and Synthesis*, 8, 144–156. <https://doi.org/10.1515/gps-2018-0042>
- Roseline, T. A., Murugan, M., Sudhakar, M. P., & Arunkumar, K. (2019). Nanopesticidal potential of silver nanocomposites synthesized from the aqueous extracts of red seaweeds. *Environmental Technology & Innovation*, 13, 82–93. <https://doi.org/10.1016/j.eti.2018.10.005>
- Roy, K., Sarkar, C., & Ghosh, C. (2014). Green synthesis of silver nanoparticles using fruit extract of *Malus domestica* and study of its antimicrobial activity. *Digest Journal of Nanomaterials and Biostructures*, 9, 1137–1147.
- Rudramurthy, G. R., Swamy, M. K., Sinniah, U. R., & Ghasemzadeh, A. (2016). Nanoparticles: Alternatives against drug-resistant pathogenic microbes. *Molecules*, 21(7), 836–865. <https://doi.org/10.3390/molecules21070836>
- Rupiasih, N. N., Aher, A., Gosavi, S., & Vidyasagar, P. B. (2015). Green synthesis of silver nanoparticles using latex extract of *Thevetia peruviana*: A novel approach towards poisonous plant utilization. *Materials Science and Technology*, 423, 012032–012040. <https://doi.org/10.1088/1742-6596/423/1/012032>
- Sabouri, Z., Sabouri, S., Moghaddas, S. S., Mostafapour, A., Gheibihayat, S. M., & Darroudi, M. (2022). Plant-based synthesis of Ag-doped ZnO/MgO nanocomposites using *Caccinia macranthera* extract and evaluation of their photocatalytic activity, cytotoxicity, and potential application as a novel sensor for detection of Pb²⁺ ions. *Biomass Conversion and Biorefinery*, 14, 8293–8305. <https://doi.org/10.1007/s13399-022-02907-1>
- Saeed, S., Iqbal, A., & Ashraf, M. A. (2020). Bacterial-mediated synthesis of silver nanoparticles and their significant effect against pathogens. *Environmental Science and Pollution Research*, 27(30), 37347–37356. <https://doi.org/10.1007/s11356-020-07610-0>
- Saratale, R. G., Shin, H. S., Kumar, G., Benelli, G., Ghodake, G. S., & Jiang, Y. Y. (2018). Exploiting fruit byproducts for eco-friendly nanosynthesis: *Citrus × clementina* peel extract mediated fabrication of silver nanoparticles with high efficacy against microbial pathogens and rat glial tumor C6 cells. *Environmental Science and Pollution Research*, 25(11), 10250–10263. <https://doi.org/10.1007/s11356-017-8724-z>
- Sastry, M., Ahmad, A., Khan, M. I., & Kumar, R. (2003). Biosynthesis of metal nanoparticles using fungi and actinomycete. *Current Science*, 85, 162–170.

- Shankar, S. S., Ahmad, A., Pasricha, R., & Sastry, M. (2003). Bioreduction of chloroaurate ions by geranium leaves and its endophytic fungus yields gold nanoparticles of different shapes. *Journal of Materials Chemistry A*, 13, 1822–1826. <https://doi.org/10.1039/b303808b>
- Sharma, S., Gangel, S., & Rauf, A. (2008). Green chemistry approach to the sustainable advancement to the synthesis of heterocyclic chemistry. *Rasayan Journal Chemistry*, 1(4), 693–717.
- Shirazi, M. S., Farimani, M. M., Foroumadi, A., Ghanemi, K., Benaglia, M., & Makvandi, P. (2022). Bioengineered synthesis of phytochemical-adorned green silver oxide (Ag_2O) nanoparticles via *Mentha pulegium* and *Ficus carica* extracts with high antioxidant, antibacterial, and antifungal activities. *Scientific Reports*, 12, 21509–21524. <https://doi.org/10.1038/s41598-022-26021-4>
- Silva, D. F., Melo, A. L. P., Uchôa, A. F. C., Pereira, G. M. A., Alves, A. E. F., Vasconcelos, M. C., Xavier-Junior, F. H., & Passos, M. F. (2023). Biomedical approach of nanotechnology and biological risks: A mini-review. *International Journal of Molecular Sciences*, 24(23), 16719–16757. <https://doi.org/10.3390/ijms242316719>
- Singh, A., Jain, D., Upadhyay, M., Khandelwal, N., & Verma, H. (2010). Green synthesis of silver nanoparticles using *Argemone mexicana* leaf extract and evaluation of their antimicrobial activities. *Digest Journal of Nanomaterials and Biostructures*, 5, 483–489.
- Singh, J., Kumar, A., Nayal, A. S., Vikal, S., Shukla, G., Singh, A., Goswami, S., Kumar, A., Gautam, Y. K., Verma, Y., Gaurav, S. S., & Pratap, D. (2024). Comprehensive antifungal investigation of green synthesized silver nanoformulation against four agriculturally significant fungi and its cytotoxic applications. *Scientific Reports*, 14(1), 5934–5949. <https://doi.org/10.1038/s41598-024-56619-9>
- Slepička, P., Slepičková Kasálková, N., Siegel, J., Kolská, Z., & Švorčík, V. (2019). Methods of gold and silver nanoparticles preparation. *Materials*, 13(1), 1–22. <https://doi.org/10.3390/ma13010001>
- Srivastav, A. L., Patel, N., Rani, L., Kumar, P., Dutt, I., Maddodi, B. S., & Chaudhary, V. K. (2024). Sustainable options for fertilizer management in agriculture to prevent water contamination: A review. *Environment, Development and Sustainability*, 26, 8303–8327. <https://doi.org/10.1007/s10668-023-03117-z>
- Stobie, N., Duffy, B., McCormack, D. E., Colreavy, J., Hidalgo, M., Hchale, P., & Hinder, S. J. (2008). Prevention of *Staphylococcus epidermidis* biofilm formation using a low-temperature processed silver-doped phenyltriethoxysilane sol-gel coating. *Biomaterials*, 29, 963–969. <https://doi.org/10.1016/j.biomaterials.2007.10.057>
- Swamy, M. K., Akhtar, M. S., Mohanty, S. K., & Sinniah, U. R. (2015). Synthesis and characterization of silver nanoparticles using fruit extract of *Momordica cymbalaria* and assessment of their *in vitro* antimicrobial, antioxidant and cytotoxicity activities. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 151, 939–944. <https://doi.org/10.1016/j.saa.2015.07.009>
- Syafuddin, A., Salmiati, M. R. S., Kueh, A. B. H., Hadibarata, T., & Nur, H. (2017). A review of silver nanoparticles: Research trends, global consumption, synthesis, properties, and future challenges. *Journal of the Chinese Chemical Society*, 64(7), 732–756. <https://doi.org/10.1002/jccs.201700067>
- Tran, Q. H., & Le, A. T. (2013). Silver nanoparticles: Synthesis, properties, toxicology, applications and perspectives. *Advances in Natural Sciences: Nanoscience and Nanotechnology*, 4(3), 033001–033024. <https://doi.org/10.1088/2043-6262/4/3/033001>
- Tumburu, L., Andersen, C. P., Rygielwicz, P. T., & Reichman, J. R. (2017). Molecular and physiological responses to titanium dioxide and cerium oxide nanoparticles in Arabidopsis. *Environmental Toxicology and Chemistry*, 36(1), 71–82. <https://doi.org/10.1002/etc.3500>
- Verma, A., & Mehata, M. S. (2016). Controllable synthesis of silver nanoparticles using neem leaves and their antimicrobial activity. *Journal of Radiation Research and Applied Sciences*, 9, 109–115. <https://doi.org/10.1016/j.jrras.2015.11.001>

- Verma, D. K., Hasan, S. H., & Banik, R. M. (2016). Photo-catalyzed and phyto-mediated rapid green synthesis of silver nanoparticles using herbal extract of *Salvinia molesta* and its antimicrobial efficacy. *Journal of Photochemistry and Photobiology B: Biology*, 155, 51–59. <https://doi.org/10.1016/j.jphotobiol.2015.12.008>
- Vijaykumar, P. P. N., Pammi, S. V. N., Kollu, P., Satyanarayana, K. V. V., & Shameem, U. (2014). Green synthesis and characterization of silver nanoparticles using *Boerhaavia diffusa* plant extract and their antibacterial activity. *Industrial Crops and Products*, 52, 562–566. <https://doi.org/10.1016/j.indcrop.2013.10.050>
- Wang, N., Sundin, W., De La Fuente, L., Cubero, J., Tatineni, S., Brewer, M. T., Zeng, Q., Bock, C. H., Cuniffe, N. J., Wang, C., Candresse, T., Chappell, T., Coleman, J. J., & Munkvold, G. (2024). Key challenges in plant pathology in the next decade. *Phytopathology*, 114, 837–842. <https://doi.org/10.1094/phyto-04-24-0137-kc>
- Weldegebrieal, G. T. (2020). Synthesis method, antibacterial and photocatalytic activity of ZnO nanoparticles for azo dyes in wastewater treatment: A review. *Inorganic Chemistry Communications*, 120, 108140–108169. <https://doi.org/10.1016/j.inoche.2020.108140>
- Wijnhoven, S. W. P., Peijnenburg, W. J. G. M., Herberts, C. A., Hagens, W. I., Oomen, A. G., Heugens, E. H. W., Roszek, B., Bisschops, J., Gösens, I., Van de Meent, D., Dekkers, S., De Jong, W. H., Van Zijverden, M., Sips, A. J. A. M., & Geertsma, R. E. (2009). Nano-silver—A review of available data and knowledge gaps in human and environmental risk assessment. *Nanotoxicology*, 3(2), 109–138. <https://doi.org/10.1080/17435390902725914>
- Yaqoob, A. A., Umar, K., & Ibrahim, M. N. M. (2020). Silver nanoparticles: Various methods of synthesis, size affecting factors and their potential applications—a review. *Applied Nanoscience*, 10(5), 1369–1378. <https://doi.org/10.1007/s13204-020-01318-w>
- Yugandhar, P., Haribabu, R., & Savithramma, N. (2015). Synthesis, characterization and antimicrobial properties of green-synthesised silver nanoparticles from stem bark extract of *Syzygium alternifolium* (Wt) Walp. *Biotech*, 5, 1031–1039. <https://doi.org/10.1007/s13205-015-0307-4>
- Zaki, S. A., Ouf, S. A., Abd-Elsalam, K. A., Asran, A. A., Hassan, M. M., Kalia, A., & Albarakaty, F. M. (2022). Trichogenic silver-based nanoparticles for suppression of fungi involved in damping-off of cotton seedlings. *Microorganisms*, 10(2), 344–361. <https://doi.org/10.3390/microorganisms10020344>
- Zhang, X. F., Liu, Z. G., Shen, W., & Gurunathan, S. (2016). Silver nanoparticles: Synthesis, characterization, properties, applications, and therapeutic approaches. *International Journal of Molecular Sciences*, 17, 1534–1567. <https://doi.org/10.3390/ijms17091534>

Chapter 14

The Toxicity of Nanoparticles and Their Impact on Plant Ecosystems



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Abstract Nanotechnology is gaining curiosity in agriculture due to its exceptional chemical and physical properties, allowing plants to modify their genetic structure, lower agrochemical levels, and enhance resistance to biological and environmental stress. Nonetheless, warnings about the ecological consequences and toxic outcomes accompanying nanoparticles have been raised because of their escalated production and usage. Due to their distinct physicochemical properties, nanoparticles can engage with soil, water, and plants, possibly leading to unexpected environmental impacts. Various harmful effects of nanoparticles on plants have been noted, including stunted growth and decreased seed germination rates. Moreover, nanoparticles impact the cellular level by disrupting the formation of chlorophyll, damaging cell membranes, and affecting the electron transport chain in the mitochondria. Nanoparticles cause DNA damage and oxidative stress at the molecular level, resulting in cell death. One major source of nanoparticle contamination is soil, which also presents a potential threat to plants and soil microbial communities. Beneficial non-target insects may also exhibit altered behavior, survival, and reproduction upon nanoparticle exposure. In addition, aquatic ecosystems are at risk as rising quantities of nanoparticles (NPs) contaminate water and trigger adverse effects on aquatic organisms. In this chapter, we have shown the harmful impacts of NPs on plant ecology. In addition, we have presented potential ways by which nanoparticles cause toxicity in different agricultural environments, illustrating the complex

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relationship between nanoparticles and soil, microorganisms, non-target insects and water pollution in agriculture.

Keywords Nanoparticles toxicity · Plant damage by nanomaterials · Nanoparticles accumulation in beneficial organisms and insects · Toxicity of nanoparticle in soil and aquatic ecosystems

14.1 Introduction

Over the past few decades, there has been accelerated production and exploitation of nanomaterials in numerous industries, which has unintentionally led to their release into the environment, causing possible threats to ecosystems and soil quality (El-Kalliny et al., 2023). Concerns about nanoparticle toxicity and ecological effects have been raised because of their escalating manufacturing and usage. Many studies have explored the possible effects of using more nanometer-sized particles and their possible impact on the environment, leading to “nano pollution or invisible pollution” (Jan et al., 2022).

Nanoparticles, when dispersed into the air, water, and soil, lead to environmental contamination and represent a significant hazard to aquatic organisms, microorganisms, humans, and vegetation (Paranjpe et al., 2013). Several nanoparticles have the potential to damage soil, disturb vital nutrient cycles, and possibly affect crop development and growth (Khanna et al., 2021). Additionally, during the treatment of surface water and wastewater, nanomaterials may interact with the soil biota, be absorbed by plants and crops, and kill both targeted and untargeted microorganisms, which might seriously impair biodiversity (Snousy et al., 2023). As a result, plants can suffer from phytotoxicity, cytotoxicity, and genotoxicity due to nanoparticles, and the safety of food is significantly compromised by the buildup of nanoparticles in edible parts of plants (Thiruvengadam et al., 2015; Muzammil et al., 2023). In addition, non-target insects are negatively impacted by the raising usage of nanopesticides. Nanomaterials can impact the growth, development, the effectiveness of parasitism or predatory behavior of beneficial insects (Li et al., 2014).

The lack of commercial applications is preventing agricultural nanotechnology research from realizing its full potential. Of the studies on herbicides, fungicides, and insecticides loaded with nanoparticles that have been published, only few have field-tested their formulations. Furthermore, only a small number of studies examined environmental problems such as soil leaching and non-target toxicity (Worrall et al., 2018).

Grasping the complex interactions between nanoparticles and the agricultural environment is crucial for implementing sustainable farming practices and ensuring the safe advancement of nanotechnology in agriculture. Additionally, it's essential to offer guidance on tackling the issues related to the practical use of nano-agrochemicals. Before their broad adoption, a comprehensive evaluation of their environmental impact, toxicity, and long-term effects is necessary (Kumari et al., 2023). It is essential for research to continue focusing on testing crop plants and

target pests, as well as performing both short-term and long-term field trials to drive innovation in agricultural nanotechnology (Worrall et al., 2018). In this chapter, we have listed the negative impacts of NPs on the agricultural environment and discussed the role that nano-pollution plays in various plant ecosystems.

14.2 Toxicity of Nanoparticles to Plants

Nanoparticles can adversely affect several stages of plant growth, such as seed germination, photosynthesis, plant metabolism, and the nutritional value of plants. They also directly interact with plants through their foliar parts (Chung et al., 2019).

Since nanoparticles are easily accumulated in plants, their consumption has negative consequences on humans that can result in heart disease, lung conditions, gastrointestinal issues, and even early death (Pui et al., 2014; Singh et al., 2024). NPs pollute plants by penetrating through the rhizosphere and roots or by passing through the shoots and leaves (Arruda et al., 2015). Plants absorb nanoparticles at a rate 15–20 times higher than that of bulk particles, and several spectral methods can detect the presence of nanoparticles in plants (Keller et al., 2018).

Studies Demonstrate that the Following Four Components are Principally Accountable for the Negative Impacts of These Materials

1. Nanoparticles can easily penetrate cell membranes and enter cells. They can therefore impair photosynthesis and interfere with a cell's normal physiological functions (Abdel-Aziz et al., 2019; Abd El-Azeim et al., 2020).
2. Certain nanomaterials, like nano-silver, nano-copper, and nano-zinc ions, can spontaneously release toxic ions (Rajput et al., 2020).
3. Damage of oxidation.
4. Bio-magnification, a process through which nanomaterials accumulate in organisms at higher trophic levels in the food chain, illustrates the impact of biological amplification (de Oliveira et al., 2015).

It is clear from scientific research that most nanoparticles are toxic to plants when they exist in high concentrations. Given their widespread industrial use, research primarily focuses on the effects of metal and metal oxide nanoparticles—such as titanium dioxide (TiO₂), silver, zinc oxide, cerium dioxide, copper, copper oxide, aluminium, nickel, and iron—on different plants. Certain non-metal nanoparticles, like fullerene and single-walled carbon nanotubes, have undergone extensive research to determine their causes of nanotoxicity (Joner et al., 2008).

Because of their exceptional functional properties, nanoparticles can alter various physiological and biochemical pathways in plant systems, including nitrogen metabolism, respiration, photosynthesis, and solute transport, etc. (Surendranath & Mohanan, 2020). NPs are functioning candidates for regulating membrane functions, acting as a modulator during cellular biochemical interactions, and serving as a gatekeeper for the entry and departure of micro- and macronutrients. Furthermore, a number of NPs have been evaluated for their capacity to regulate physico-chemical

pathways related to plant biota (Surendranath & Mohanan, 2020). In addition, the unique physicochemical properties of nanoparticles enable them to easily interact with biomolecules and biological pathways. Consequently, they can induce oxidative stress, which may lead to genotoxicity and disrupt plant growth.

The toxicity of nanoparticles can harm plants in several ways shown in (Fig. 14.1). Because of their tendency to aggregate, nanoparticles may result in stomatal closure (Gao et al., 2023). Following their interaction with and disrupting cell wall pores, nanoparticles enter the cytoplasm via endocytosis and interact directly with organelles like mitochondria, chloroplasts, and the endoplasmic reticulum. Nanoparticles that penetrate nuclear membranes can directly affect DNA and histones (Zafar et al., 2023). The potential mechanisms of nanoparticle-related toxicity in plants may involve overproduction of reactive oxygen species (ROS), oxidative stress, increased antioxidants, damage to lipids and DNA, changes in primary and secondary metabolism, disruption of phytohormone signaling, and alterations in signal transduction. Ultimately, these processes may collapse the plant's defense mechanism, resulting in necrosis or apoptosis (Fig. 14.1) (Hossain et al., 2015).

Determining the toxicity of nanoparticles can be considerably easier with more knowledge of how they affect plants (Table 14.1).

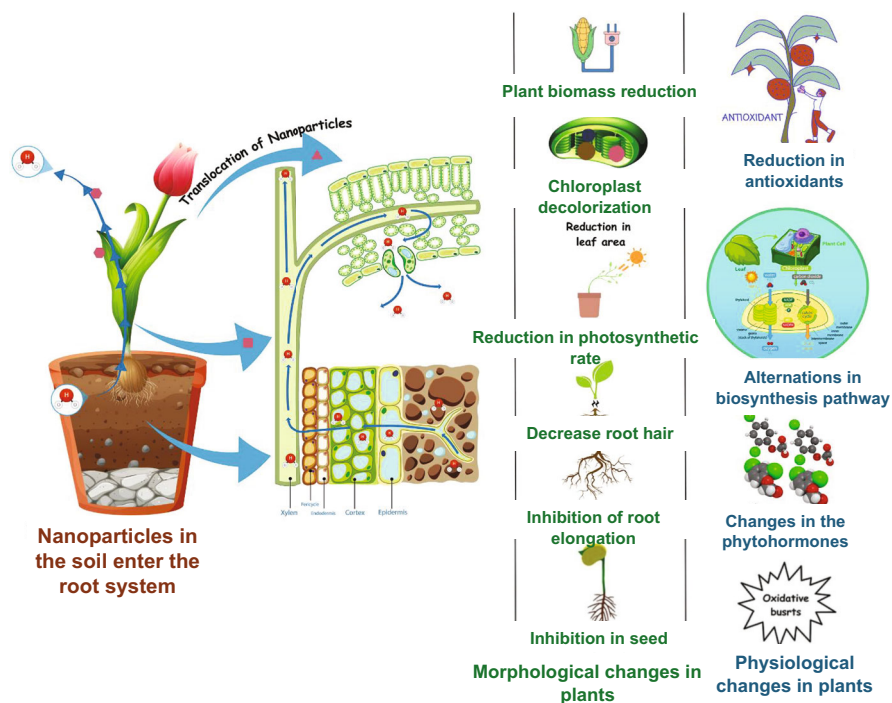


Fig. 14.1 Plant toxicity due to nanoparticle exposure. (Thiruvengadam et al., 2024)

Table 14.1 Toxicity of different nanoparticles on treated plants

Nanoparticle	Plants	Negative impact	Reference
AgNPs	<i>Allium cepa</i> L. <i>Eruca sativa</i> L.	ROS production, DNA damages, proteins modification for redox regulation	Vannini et al. (2013)
Al ₂ O ₃ NPs	<i>Triticum aseivum</i>	Increase of H ₂ O ₂ content, reduction of photosynthetic pigments	Yanik and Vardar (2015)
TiO ₂ NPs	<i>Zea mays</i>	Suppression of germination, and the growth of roots and shoots	Fellmann and Eichert (2017)
(Co ₃ O ₄) NPs	<i>Solanum melongena</i> L.	Damage to DNA and mitochondria, induction of oxidative stress, and triggering of cell death	Faisal et al. (2016)
Cuo NPs	<i>Oryza sativa</i>	Reduction in plant biomass accumulation, activation of oxidative stress markers, and extensive damage to stomata and cellular ultrastructure	Azhar et al. (2023)
CeO ₂ NPs	<i>Nicotiana tabacum</i>	Generation of reactive oxygen species (ROS), mitochondrial dysfunction, and, eventually, cell death	Sadhu et al. (2018)
ZnO NPs	<i>Allium cepa</i> L.	Cytotoxicity in the meristematic cells of root tips causes loss and damage to membrane integrity, along with reductions in chlorophyll and carotenoid levels and increased lipid peroxidation.	Ghosh et al. (2016) and Zoufan et al. (2020)
FeO NPs	<i>Raphanus sativus</i> L.	Increasing ROS generation, stimulating mitochondrial transmembrane potential, raising calcium and nitric oxide influx, intensifying lipid and DNA damage, and elevating levels of SOD and CAT.	Saquib et al. (2016)
(PBS NCs) Polybutylene succinate nanocrystals	<i>Zea mays</i>	Imposes phytotoxic effects by penetrating the cell wall into the intercellular space and accumulating in the cytoplasm, which impacts seed germination and root elongation.	Ullah et al. (2020)
Polystyrene NPs	<i>Allium cepa</i> L.	Chromosomal aberrations, nuclear abnormalities and destruction of genomic stability	Maity et al. (2020)

The toxicological impacts of nanomaterials is affected by their physiochemical properties and factors like plant species, growth stages and growth medium, the exposure duration and methods of nanoparticle introduction and interaction.

There are several methods for exposing plants to nanoparticles (NPs) (Fig. 14.2), including directly injecting nanoparticles into plant tissue, spraying nanoparticles onto the leaves or other plant parts, incorporating nanoparticles into the soil, irrigating plants with nanoparticle solutions, and contaminating cellular pollen or seeds (Yang et al., 2017; Yan & Chen, 2019).

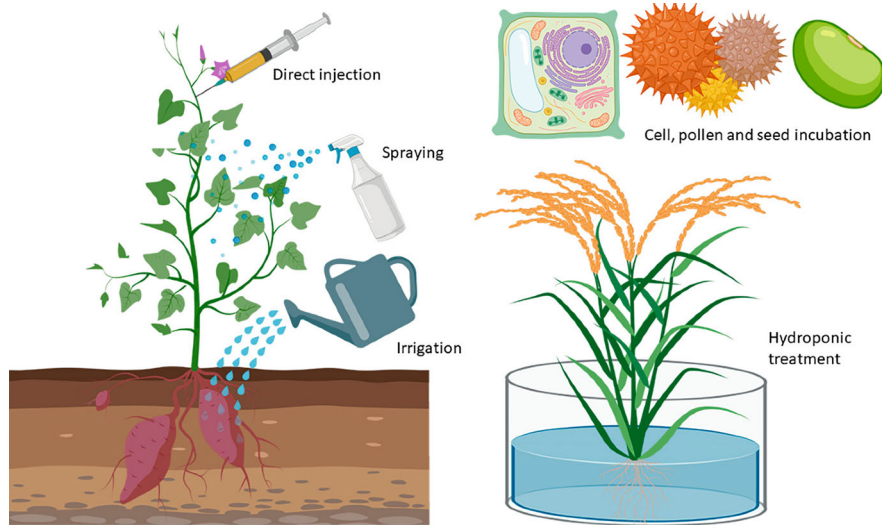


Fig. 14.2 Different types of nanoparticles (NP)/plant exposure methodologies. (Yan & Chen, 2019)

Researchers have created comparable solutions to address the toxicity that nanoparticles cause. These solutions effectively reduce toxic substances generated by nanoparticles by adding a surface coating (Sturikova et al., 2018).

14.2.1 Inhibitory Effect of Nanoparticles on Seed Germination and Plant Growth

Inhibition of germination, elimination of shoot elongation, and even plant death are just a few of the detrimental effects that NPs can have on plants (Muzammil et al., 2023). Seed germination is essential for production, and several studies have demonstrated how the toxicity of nanoparticles can limit the germination of seeds (Raliya et al., 2016). ZnO NPs and zinc NPs (at 2000 mg/L) treatments dramatically reduced the germination of seeds in maize and ryegrass, respectively (Lin & Xing, 2007). Another study found that when TiO₂ NPs were treated at concentrations of 0.01, 1, and 10 mg/mL, the germination process of seeds decreased (Jalill & Yousef, 2015; Wu et al., 2019). The study assessed the phytotoxic effects of different metal oxide nanoparticles on the seeds of cucumber, lettuce, and radish plants (Wu et al., 2012). The results showed that exposure to NiO and CuO NPs significantly reduced the germination of the seeds in all three plants. The negative effect was ascribed to the NPs adhering to the seed surface after the release of unbound metallic ions. Studies have shown that zinc NPs and zinc ions prevented plants from growing in their first

stages; the former prevented the formation of elongation zones, while the latter had harmful effects on meristem cells (Wu et al., 2019).

In addition to delaying seed germination, NPs may also adversely affect other plant growth characteristics such as biomass, shoot and root elongation, and leaf number (Muzammil et al., 2023). According to many investigations, exposure to nanoparticles has been linked to a notable decline in plant growth. High quantities of nanoparticles sprayed onto leaves of plants cause a considerable accumulation on the leaf surface, obstructing stomata and impeding plant gas exchange and photosynthesis. However, In some plants, as opposed to shoots, the root is the main organ for absorbing nanoparticles from the soil or water (Tripathi et al., 2017; Vinković et al., 2017).

NPs have been shown to affect plant development by interfering with photosynthesis, causing oxidative damage, altering the activity of antioxidant enzymes, and unbalancing the nutrient composition of edible crops; consequently, they might reduce root and stem length (Lian et al., 2020). Nanoparticles transform in plants, damage cell structure and decrease nutrient uptake and delivery (Fedorenko et al., 2021). Additionally, the toxicity of CuO NPs in *Arabidopsis* seedlings, significantly decreased the weights and root lengths of the plants (Shaw & Hossain, 2013). Additionally, when ZnO NPs were studied for their toxic effects on *A. thaliana*, researchers discovered that high particle concentrations resulted in chlorosis and reduction of leaf size, as well as inhibition of lateral roots. This inhibition of lateral root growth may be due to the suppression of nutrient absorption in roots, which lowers the level of micronutrients (Nair & Chung, 2017). The findings also demonstrated that following treatment, the biomass, carotenoid content, and chlorophyll content of seedlings, all dropped, photosynthesis was impeded, and the minerals zinc and iron were reduced (Tripathi et al., 2017). (Mirzajani et al., 2013) found that at lower concentrations (30 $\mu\text{g/mL}$), silver nanoparticles (Ag NPs) could not penetrate the roots of *Oryza sativa* (rice), but at greater concentrations, they induced toxicity and destroyed the cell structure. When exposed to Cadmium sulfide nanoparticles (CdS NPs) at concentrations of 125, 250, 500, and 1000 mg L^{-1} , respectively, the root elongation of *A. thaliana* was significantly reduced compared to the control group. This suggests that the phytotoxicity induced by CDs increased in a dose-dependent manner (Chen et al., 2018).

In this context, prolonged plant exposure to polymer nanoparticles can lower the rate of germination, mostly because the particles' obstruction of plant pores reduces the plants' ability to absorb nutrients (Boots et al., 2019; Bosker et al., 2019; Wang et al., 2023). In addition, polystyrene nanoparticles with various surface charges can affect plant growth by reducing stem and root length and fresh weight. The inhibition is more noticeable the higher the concentration of nanoparticles (Sun et al., 2020).

The multi-walled carbon nanotubes (MWCNTs) severely affected the lengths of roots and shoots in *Oryza sativa* seedlings (Hao et al., 2016). Moreover, oxidized multi-walled carbon nanotubes (MWCNTs) notably reduced biomass production and growth in mustard plants (Mondal et al., 2011). When multiwalled CNTs and C60 fullerenes were introduced to *Glycine max* and *Zea mays*, similar harmful effects were noted, and there was a notable drop in plant biomass (De La Torre-

Roche et al., 2013). According to the aforementioned findings, NPs can impede photosynthesis and lower nutrient content, which can lead to phytotoxicity and prevent plants from germinating and growing. NPs have the potential to break down the cell structure of plants by penetrating their cell walls.

14.2.2 Oxidative Stress Damage of Nanoparticles in Plants

After entering plants, NPs have the ability to directly alter the structure of cells, molecules, and membranes. They may also have an impact on the plant's defense mechanism. In addition, due to their solubility and production of reactive compounds, NPs may have unanticipated consequences (Navarro et al., 2008). When nanoparticles and plants interact, more ROS are produced in the plants, which can cause oxidative damage and genetic toxicity (Marslin et al., 2017). ROS formation in plants has been linked to a variety of effects, including increased oxidative damage, lipid peroxidation, altered ion transport across cell membranes and damage to cell membranes both intracellularly and extracellularly (Auffan et al., 2008; Wang et al., 2012). Additionally, the production of ROS in plants due to NP exposure damages DNA by breaking its strands or causing point mutations that cause the expression of death receptor genes (Yang et al., 2017). Lipid peroxidation destroys the cell membrane, causing ion leakage, degradation of the cell metabolism, and eventual cell death (Sadżak et al., 2020). It causes intracellular Ca_2^+ ions to leak out, which is followed by mitochondrial disruption and malfunctioning of several encoded proteins (Mushtaq et al., 2020). Because oxidative stress causes a large number of reactive oxygen species (ROS), it disrupts several metabolic reactions in plants and results in a decrease in gas exchange and photosynthetic activity (Adrees et al., 2015).

Plants exposed to extremely low concentrations of NPs produce an excessive amount of ROS (Ali et al., 2020). Cells enter a condition of "oxidative stress" when reactive oxygen species (ROS) levels surpass defense mechanisms. This state leads to irreversible damage to cell membranes' proteins, nucleic acids, and lipids. The oxidative burst toxicity of nanomaterials causes membrane disruption, chloroplast disarray, a reduction in photosynthetic activity, cell injury, and altered gene expression (Mullineaux et al., 2018). Like other aerobic organisms, plant cells react to changes in their surroundings by releasing reactive oxygen species (ROS). At low concentrations, ROS activates the defense signal; at high concentrations, it causes oxidative damage (Gao et al., 2023).

By producing antioxidant enzymes and low molecular weight antioxidants, plants can protect their cells and subcellular structures from the damaging effects of active oxygen (Qamer et al., 2021). Therefore, research on oxidative damage caused by nanoparticles primarily focuses on analyzing ROS concentration and antioxidant enzyme activity. Plants have antioxidant systems and ROS scavenging pathways to endure various stresses (Czarnocka & Karpiński, 2018).

14.2.3 *The Cytological and Physiological Toxicity of NPs in Plants*

Cytotoxicity is caused by nanoparticles either directly producing reactive oxygen species (ROS) or indirectly stimulating the cellular redox system, which in turn amplifies ROS creation through a Fenton-type reaction. The production of ROS therefore impacts the respiratory electron transport chain in the mitochondria, deactivates photosystems I and II in chloroplasts, and finally results in cytotoxicity (Karami Mehrian & De Lima, 2016). Certain nanoparticles have the ability to reduce photosynthetic machinery, change IAA production, and modify carbon signaling pathways (Xiao et al., 2021) (Table 14.1).

It was shown that the co-exposure of AgNPs and nanoplastics causes agglomeration, influences the distribution and absorption of metals, such as iron, calcium, magnesium, and potassium, causes oxidative stress, and activates antioxidants. In addition, AgNPs control cell metabolism by binding to calcium channels, receptors, and calcium-sodium ATP pumps. AgNPs control calcium signaling and are implied in cell division apoptosis (Mishra et al., 2014).

Important toxicity markers in plants are the quantity and activity of phytohormones (Gangwar et al., 2014; Muzammil et al., 2023). It is known that various stressors can cause different hormonal pathways to become activated or downregulated (O'Brien & Benková, 2013). Plant hormone balance is impacted by nanoparticles, as evidenced by the increase in cytokinin levels in *Capsicum annuum* in response to AgNP stress and the decrease in IAA and ABA in a cotton plant in reaction to CuO NP (Muzammil et al., 2023). (Bleecker & Kende, 2000) revealed that the presence of silver ions decreased the synthesis of ethylene, weakening the interaction between ethylene and indole acetic acid (IAA). In addition, it was observed that when rice seeds were subjected to carbon nanotubes, phytohormone's concentration was reduced (Hao et al., 2016). (Nhan le et al., 2015) observed that following exposure to Fe₂O₃ NPs, the levels of gibberellic acid (GA) and abscisic acid (ABA) in leaves were considerably lower in traditional cotton.

Another useful indicator of a plant's general health is photosynthesis (Kalaji et al., 2014). Various studies have demonstrated that nanoparticles influence the concentration and activity of photosynthetic pigment in plants (Perreault et al., 2014; Tripathi et al., 2017). Plant growth inhibition or even plant death could arise from a highly concentrated nanoparticle concentration that negatively impacts photosynthesis. (Yang et al., 2022) suggested that AgNPs generated toxic stress in plants by causing modifications to the main metabolites, such as sugars, alcohols, amino acids, and sugar alcohols. Furthermore, volatile substances such terpenoids, aldehydes, and alkanes changed. Determining the cytotoxicity of nanoparticles in plants and developing strategies to lessen their adverse effects require an understanding of these mechanisms and pathways (Thiruvengadam et al., 2024).

14.2.4 Genotoxicity of Nanoparticles

Because of their tiny size, NPs have the ability to infiltrate cells and influence how genes are expressed differently. Plants of different kinds exhibit these alterations following NP exposure: errors in cell division, damage to DNA, aberrant chromosomes, and dysregulation of micro-RNA. DNA damage can be induced by nanoparticles through direct and indirect mechanisms. Broadly speaking, genotoxicity mechanisms can be classified as either direct or indirect. The physical interaction between NPs and DNA causes direct genotoxicity, but an increase in ROS level or a decrease in DNA repair could cause indirect genotoxicity (Jogaiah et al., 2021).

In the first route, nanoparticles reach the nucleus directly and interact with the DNA strand to prevent transcription and replication. In the second pathway, nanoparticles induce oxidative stress, triggering an oxidative burst that prompts the entry of nanoparticles into the nucleus and induces a sequence of cellular events that ultimately lead to the destruction of mitotic spindles and nuclear proteins, which in turn causes damage to DNA and apoptosis (Muzammil et al., 2023).

Typically, genotoxicity mechanisms are categorized into direct and indirect types. Direct genotoxicity results from nanoparticles physically interacting with DNA, while indirect genotoxicity may stem from reduced DNA repair or elevated ROS levels.

Metal-based nanoparticles alter and release toxic metal ions into plants, leading to DNA and protein oxidation and disrupting normal cell functions. According to (Moazzami Farida et al., 2020), plant cell division may be impacted by the genotoxicity of nanoparticles that interact with biological macromolecules like lipids and nuclei.

Ag nanoparticles, for instance, have been demonstrated to disrupt regular cell division, impede DNA synthesis, and result in chromosome abnormalities when internalized in wheat root tips (Abdelsalam et al., 2018). Silver nanoparticles induced chromosomal aneuploidy, micronuclei formation, chromosome loss, chromosomal abnormalities, binucleate cells, sticky chromosomes, and chromosomal fragment distortion (Abou-Zeid & Baraka, 2014). These nanoparticles decreased the mitotic index in the root tips of *faba beans* (Patlolla et al., 2012).

CuO NPs also caused changes in the rice's root-growth-related genes. They have also been discovered to be responsible for radish and ryegrass DNA damage. CuO NPs increased the abnormality index and lowered the mitotic index in onion roots (Atha et al., 2012). Additionally, chromosomal aberrations (including aggregation and lagging chromosomes), spindle deformation, and nuclear abnormalities were noted, resulting in genomic instability and illustrating the genotoxic effects of polystyrene nanoparticles on onion cells (Maity et al., 2020).

14.2.5 Toxic Effects of Nanoparticles on Crop Quality

NPs have a significant impact on the quality and quantity of food crops grown in soil within their surroundings (Atha et al., 2012). CeO₂ NPs were toxic to rice plants due to their reduction of nonreducing sugars, phenolics, fatty acids, and amino acids (Rico et al., 2013). Following the application of CeO₂ NPs, transgenic cotton showed similar harmful effects and a decrease in the concentration of micronutrients, such as magnesium, zinc, iron, and phosphorus. Additionally, Au NPs changed the reducing sugars in mustard seeds (Antisari et al., 2015). According to reports, engineered nanoparticles (ENPs) have a significant impact on a plant's carbohydrate content (Mondal et al., 2011), proteins (Gao et al., 2008), phenolic content, and nutritional components (Speranza et al., 2010).

14.3 Nano Pollution in Soil

Soil significantly contributes to nanoparticle contamination. Nanopollution arises from the increased production and use of nanoparticles, as well as the direct or indirect disposal of various sewage wastes and sludge into soil through landfills (Adhikari & Dharmarajan, 2022), which can potentially be toxic to soil organisms and plants. Once in the soil, NPs are dispersed across the organic phases, minerals, and soil solution through coulombic or covalent bonding interactions with soil colloids. Understanding the eco-toxicological effects of nanopollutants requires an analysis of the properties of both soil and nanoparticles, which affect bioavailability (Stone et al., 2010).

Soil properties, such as ionic strength, the amount of dissolved organic matter, and chemical and biological processes, can all have an impact on the suspension of these nanoparticles (Delay & Frimmel, 2012; Nowack et al., 2012; Zou et al., 2015; Li et al., 2016). The soil's enzymatic activity, type, and concentration all affect how nanoparticles interact with it (Joško et al., 2014). Agglomeration, dissolution, and leaching of nanoparticles in soil are influenced by a number of variables, including the chemical makeup of the soil, humidity, pH, electrical conductivity, and clay content (Petosa et al., 2010). Soil clays have negative sites that enable the electrostatic adsorption of nanoparticles on the soil surface (Auffan et al., 2009).

The distribution of artificial nanoparticles in soils leads to changes in aggregate size, suspension stability, transport, and bioavailability (Santiago-Martín et al., 2016). Thus, investigating the colloidal processes of engineered nanoparticles is crucial for understanding their behavior and associated risks (Philippe & Schaumann, 2014; Sharma et al., 2015). According to (Phenrat et al., 2009), when nanoparticles aggregate to a bulk size, they alter their action, promote lethality, and intensify soil hazards. In addition, nanoparticles can be coated with dissolved organic matter, leading to modifications in their surface characteristics including pore size distribution, specific surface area, sorption qualities to organic pollutants,

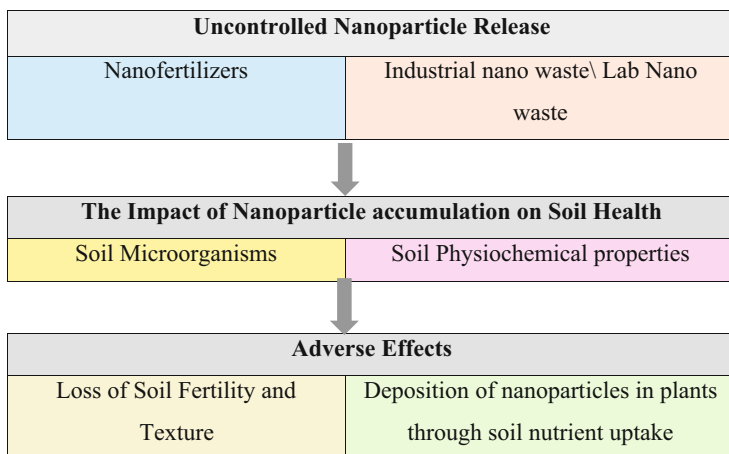


Fig. 14.3 An overview of the effects of nanoparticles on soil health and related ecosystems. (Mishra, 2019)

aggregation state, and mechanisms of toxic effects. It is shown unequivocally and persuasively that the stability of metal-based nanoparticles in water suspension was enhanced by dissolved organic materials (Li et al., 2016). Another factor influencing how nanoparticles transport through soil is temperature (Mishra et al., 2014). As stated by (Gupta & Xie, 2018), the physical and chemical transformations that nanoparticles go through can cause them to lose their initial properties, which can impact their toxicity and bioavailability. Because of their interactions with different organisms such as microorganisms, plants, and human (through the food chain), nanoparticles present in soil eventually have an impact on cell formation and growth (Medina-Pérez et al., 2019). Several NP forms have been identified in recent research investigating nanopollution in soil ecosystems as major contributors to potential environmental repercussions. (Fig. 14.3).

There is evidence that soil's microscopic characteristics, such as the amount of humic acid and the bacterial community, are impacted by nanoparticles (Ben-Moshe et al., 2013). Once discharged into the environment, nanoparticles can impact plant development and microbiological diversity (Kumar et al., 2012). According to (Gupta & Xie, 2018)- Nanoparticles can impact microbiological organisms besides plants, such as bacteria and fungi. Additionally, soil fertility and self-cleaning rates are impacted by nanoparticles, which also have an impact on the balance of nutrients and plant nutrition (Janvier et al., 2007). Furthermore, the activity of soil enzymes like phosphatase, dehydrogenase, and beta-glucosidases are reduced by nanoparticles (Kim et al., 2013; Joško et al., 2014).

Among the notable pollutants found in soil are silver nanoparticles (AgNPs), copper nanoparticles (CuNPs), zinc oxide nanoparticles (ZnO NPs), and titanium dioxide nanoparticles (TiO₂ NPs) (Khan et al., 2021). Metal nanoparticles (NPs) are widely used in a variety of industrial and consumer applications. Their distinct physicochemical properties can have an impact on soil health. Moreover, due to

their extensive application and potential persistence in soil environments, carbon-based nanoparticles like carbon nanotubes (CNTs), fullerenes (C60 and C70), and graphene nanoparticles (NPs) have garnered interest (El-Kalliny et al., 2023). It was discovered that adding titanium dioxide (TiO₂) nanoparticles to soil can lower its pH while raising its carbon content overall (Fang et al., 2009). The ability of the soil to combine phosphorus would subsequently be impacted by those pH value fluctuations, which would either encourage or restrict plant growth.

After entering the soil, the designed nanomaterials may have an impact on the pH, enzymes, and organic matter in the soil (Fang et al., 2009). Once in the soil, engineered nanomaterials may interact with a variety of organic ligands and change the surrounding environment in a number of ways. Soil organic matter is a common component that can be adsorbed onto the surface of the engineered nanomaterials and soil particles through hydrophobic, hydrogen bonding, and electrostatic interactions, changing the stability and dispersion of the created nanomaterials. These modifications to soil adsorption behavior and engineered nanomaterial stability would subsequently impact the toxicity, mobility, and direction of the engineered nanomaterials (Liu et al., 2020). Humic acid is an organic substance found in soil that gives adsorbed nanoparticles a negative charge, improving their stability and reducing the amount of engineered nanomaterials that agglomerate and precipitate (Fang et al., 2009).

Understanding how nanoparticles interact with soil components is essential for determining their environmental fate and devising strategies to mitigate their harmful effects on soil ecosystems. Researchers are still needed to create new methods for keeping an eye on the potential toxicity of nanoparticles and to assess the advantages or disadvantages for relevant soil science species, such as bacteria, fungus, plants, and other living things (Mura et al., 2013).

14.4 Nanoparticles and Soil Biota

Negative effects on soil microbial populations are one of the most researched attributes of NMs applications in soil. Many aspects of how nanomaterials interact with soil microbial biota are unknown, with only a small number of consequences identified (Kannan et al., 2020). As micro-organisms play a significant role in regulating and maintaining the general health and function of an ecosystem (Janvier et al., 2007), alterations in the microbial community will significantly impact the ecosystem (Kanerva et al., 2008). To address the environmental and health concerns associated with the production and use of nanomaterials, a deeper understanding of how microorganisms respond to nanoparticles and nanomaterials is essential (He et al., 2011).

Applications of metal-based engineered nanomaterials adversely impacted plant-fungi and plant-bacteria interactions, as well as bioaccumulation, biomagnification, soil nitrogen turnover, and carbon emissions, ultimately leading to a reduction in microbial populations. (McKee & Filser, 2016). Some reports indicated that two

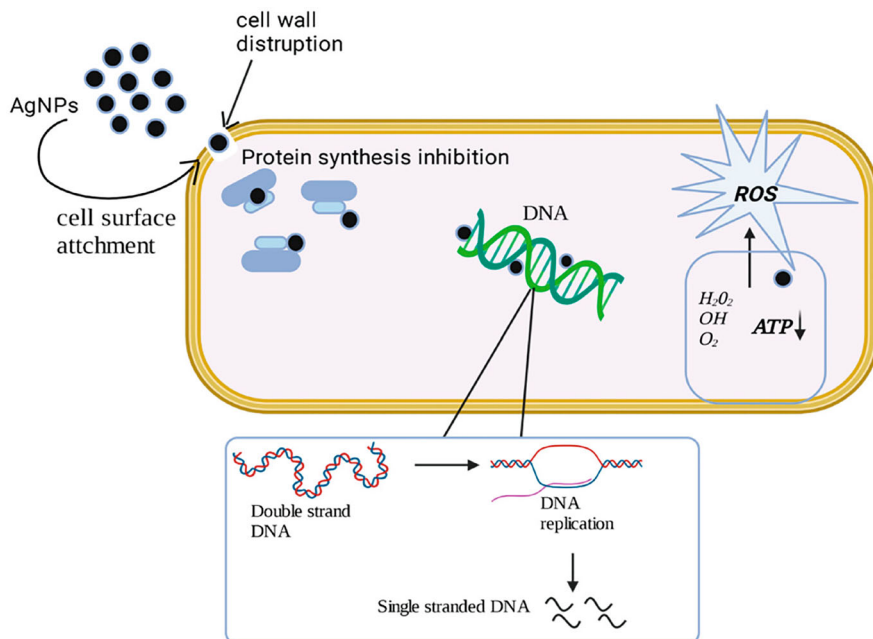


Fig. 14.4 The nanoparticle's toxicity towards bacterial cell. (More et al., 2023)

phases have been proposed as being involved in the interaction between the nanoparticles and the bacterial cell that causes cytotoxicity (Kumari et al., 2014) (Fig. 14.4). During the **first phase**, the cell membrane experiences oxidative damage from the nanoparticles, which leads to a loss of membrane integrity but no significant decline in cell viability. Furthermore, the nucleus and other cell organelles are harmed **in the second step** when the nanoparticles leak out of intracellular components, which is the main reason for decreased viability and internalization (Klaine et al., 2008; Kumari et al., 2014). Despite the fact that bacteria have evolved resistance and avoidance mechanisms against nanoparticles, more focused research is required to determine the absorption processes and effects in soil and microbes related to beneficial soil microbes such as phosphate solubilizers, arbuscular mycorrhizal fungus, and N_2 -fixing bacteria (Thul & Sarangi, 2015). The impact of multiwalled carbon nanotubes (MCNT) on the diversity of rhizospheric microbial communities was demonstrated in a study by (Chen et al., 2022). They showed that MCNT adversely affects the availability of potassium and nitrogen and impacts the taxonomic compositions of soil microbes.

Certain researchers attribute the notable alteration in the soil microbial community to metal nanoparticles (NPs), particularly those of highly dissolved heavy metals. CuO NPs negatively affect N fixing in the bacterial community by considerably altering the genes *norB* and *nosZ* (engaged in denitrification) in bacteria (Tripathi et al., 2023). ZnO NPs impact *Azotobacter* species' thermogenic

metabolism, which is important in nitrogen fixation (Chai et al., 2015). They also affect the activity of urease, catalase, and fluorescein diacetate hydrolysis enzymes in phosphorus and potassium-solubilizing bacteria. Due to their harmful impact on heterotrophic bacterial and fungal populations, ZnO nanoparticles are also considered to hinder N mineralization (Rashid et al., 2017).

The bacterial cell wall is adhered to by nanoparticles, which then enter the bacterial cell and modify its metabolic processes. It has an impact on protein synthesis and DNA replication, oxidative stress causes ROS production. Moreover, in the end, it results in cell death. Cyanobacteria are the largest nitrogen fixers globally due to the presence of *nif* gene and other perfect traits. They are capable of fixing the atmospheric nitrogen themselves and act as biofertilizers, which greatly contribute to the growth of foliage. The eco-toxicological study conducted by (Brayner et al., 2010), examined the effects of ZnO nanoparticles on the photosynthetic activity of cyanobacteria *Anabaena flos-aquae* and *euglenoid microalgae euglena gracilis*. The results showed that ZnO nanoparticles cause stress, which leads to a progressive reduction in the photosynthetic rate and ultimately to cell death.

According to (Tripathi et al., 2023), exposure to engineered nanomaterials causes a dramatic shift in the functional variety and abundance of soil microbial populations. Plant growth-promoting rhizobacteria (PGPR) such as *Pseudomonas aeruginosa*, *Pseudomonas putida*, *Pseudomonas fluorescens*, and *Bacillus subtilis*, along with soil nitrogen cycle bacteria like nitrifying and denitrifying bacteria, have exhibited varying levels of inhibition when exposed to engineered nanoparticles (ENPs). It is assumed that iron and copper-based nanoparticles react with environmental peroxides to produce free radicals, which are extremely toxic to microbes like *P. aeruginosa* (Saliba et al., 2006). Similarly, nanoparticles have a negative impact on eukaryotic development and metabolism. The toxic effects of ZnO nanoparticles on unicellular fungi, such as yeast (*Saccharomyces cerevisiae*), have been demonstrated by (Kasemets et al., 2009). ZnO nanoparticles were harmful to free-living *Protozoan* Sp. (*Tetrahymena thermophila*) (Mortimer et al., 2010).

Single-walled carbon nanotubes (SWCNTs) have been shown to have an impact on the biomass of soil fungus, which are crucial for nutrient recycling because they are the major decomposers of soil organic matter (Rodrigues et al., 2013). Additionally, it has been found that introducing ZnO NPs has a deleterious impact on soil fungi (Rashid et al., 2017). When considered as a single system, soil microbial biomass carbon (SMBC) plays a critical role in determining the balance of soil carbon release and sequestration in the plant-soil microbial environment (Thakur et al., 2015). According to (Antisari et al., 2015), exposure to nanoparticles like Ag NPs, Ni NPs, and Co NPs has been shown to significantly reduce SMBC.

14.5 Nanopollution in Water

Nanomaterial testing in water treatment have garnered a lot of attention the past decade due to their versatility. But it's impossible to ignore the extremely little number of published research on these nanomaterials' toxicity when used in the water treatment sector (Gehrke et al., 2015). Because of the detrimental effects that increasing concentrations of nanoparticles (NPs) on aquatic organisms, aquatic habitats are in danger (Lekamge et al., 2020).

The application of nanotechnology in water treatment is over exaggerated; the benefits are essentially theoretical hypotheses, while the drawbacks are fairly certain. The problem arises from the use of really fundamental hypotheses and laboratory findings generated under controlled experimental settings (Ouyang et al., 2022). Water treatment using nanoparticles is questionable in natural environments due to the selectivity of contaminants removal and the properties of the nanomaterial itself. Surface water-waste water treatments can cause serious issues for biodiversity since nanomaterials can interact with the soil biota, be absorbed by plants and crops, and kill both targeted and untargeted microorganisms. Regarding the fate, transport, bioavailability, and bioaccumulation of nanomaterials in complex aquatic settings, there is a lack of precise information. As the number of sources and applications for engineered nanoparticles expands, there is also increasing uncertainty regarding the potential environmental concerns associated with their discharge into the environment (Lekamge et al., 2020). For instance, fish and plants can have detectable toxicological effects when exposed to cerium-oxide nanoparticles, yet the same organisms are not significantly affected by gold or silver nanoparticles. Since natural inorganic nanoparticles are so common, new techniques to classify them as inorganic water pollutants are desperately needed in order to better understand their fate and possible consequences on ecological environments (Malakar & Snow, 2020; Snousy et al., 2023).

According to (Das et al., 2018) reports that CNTs may be toxic because of their tendency for reactivity with different proteins found in the water system, which could lead to toxic effects in the aquatic environment. The toxicity of colloidal nanomaterials (Ncs) to aquatic creatures has been the subject of certain investigations, most of which have been conducted in lab environments (Snousy et al., 2023). In addition, (Yan & Chen, 2019) studied the trophic transfer of AgNPs in aquatic environments and focused on algae as the fundamental trophic level. This research has demonstrated that nano-Ag generated from AgNPs can accumulate inside microalgae. The bioaccumulation and trophic transmission of AgNPs in a simplified freshwater food chain involving *Daphnia magna* and *Chlorella vulgaris* (a keystone organism common in freshwater habitats and a long-standing model organism in aquatic ecotoxicity research), were investigated by (Kalman et al., 2015). *Daphnia magna* was given the Ag-contaminated algae once AgNPs had accumulated in them. Additional investigation revealed that food is the dominant pathway route of Ag uptake in *Daphnia magna*.

The toxicity of Nano colloids (Ncs) in water, as well as its physical and chemical characteristics, can be greatly impacted by complex matrix presence and environmental fluctuations in natural water, according to (Ouyang et al., 2022). They indicated that the behavior of Ncs in the complex environmental processes of natural water and their interactions with aquatic life are currently poorly understood. The quantity, concentration, composition, and morphology of Ncs in various natural water bodies can affect how toxic they are, but they lacked the comprehensive information and mechanisms to completely understand this relationship. Much more research is still required in this area to assess the sustainability of nanoengineered materials on all fronts, even though they offer the potential for innovative water technologies that can be readily adapted to customer-specific applications and integrated with other current technologies (Yang et al., 2019).

14.6 Toxicity of Nanoparticles on Beneficial Insects

Beneficial insects are essential parts of the food chain and provide an advantage for preserving the agroecosystem's natural balance. Pollinators, weed eaters, natural enemies, productive insects (such as honeybees, silkworms, and lac insects), scavengers, and decomposers are within the group of beneficial insects (Capinera, 2005; Kannan et al., 2020).

Non-target insects suffer from the expanding application of nanopesticides. Effective beneficial insects can be affected by nanomaterials in terms of their growth, development, efficiency as parasites or predators, and adult emergence. The disruption of membranes, oxidation of proteins, genotoxicity, disruption of energy transduction, production of reactive oxygen species, and release of toxic substances are among the toxicity mechanisms of nano inputs on beneficial insects in agricultural ecosystems. For instance, silver nanoparticles (Ag NPs) can be toxic through a variety of processes, including surface adhesion and modification of membrane characteristics that impact permeability and cell respiration. They can also release toxic Ag⁺ ions and damage DNA. Titanium dioxide nanoparticles (TiO₂NPs) were investigated in another study that revealed how they reduced the molting and development period of *Bombyx mori* (Lepidoptera: Bombycidae) (Li et al., 2014).

Oxidative stress caused by nanoparticles has been linked to the production of free radicals and reactive oxygen species (ROS), which can lead to a range of reactions in different insect cell types, including apoptosis, lipid peroxidation, depletion of glutathione, mitochondrial activity reduction, apoptosis, and oxidative stress (Canesi et al., 2012). According to (Rai et al., 2014), insects are damaged by nanoparticles because they can penetrate their exoskeleton and enter the intracellular region. Once inside, the nanoscale material attaches to either phosphorus or sulfur in DNA or proteins, rapidly denaturing organelles and enzymes. Cell death and loss of cellular function result from disruptions in the proton motive force and a decrease in membrane permeability (Jiang et al., 2015; Benelli, 2016).

Common natural predatory dragonflies' behavior, survival, and ability to reproduce were all affected by exposure to low concentrations of silver nanoparticles (Brausch et al., 2011). Ag nanoparticles (NPs) exposure have been linked to changes in behavioral features and the natural predatory life cycle, according to (Pokhrel & Dubey, 2012).

Likewise to this, (Kannan & Elango, 2019) investigated the impact of silica nanoparticles at varying doses on the potential for green lacewing (*Esben-Peterson*) eggs to emerge. They found that, in comparison to the untreated control (96.51%), the emergence rate was only 29.41% at 20000 and 15,000 mg/l.

According to (Borsuk et al., 2013) research, adding 25 mg/l of nano silver to bee food had a detrimental effect on honeybees by decreasing worker longevity under lab conditions, and the feeding rate was lowered by the high concentrations of ZnO NMs (Glavan et al., 2017). Moreover, ZnO NMs may result in decreased lifespan, increased AChE and GST activities, and metabolic impairment (a reduction in the level of brain protein overall). That might suggest that ZnO NMs have a major impact on the bees' neural system (Milivojević et al., 2015). According to (Özkan et al., 2014), the harmful effect of Ag-TiO₂, ZnO-TiO₂, and TiO₂ nanoparticles on *Apis mellifera* increased as their concentration and exposure duration rose. Bees exposed to cerium (IV) oxide nanoparticles (nCeO₂s) orally over a longer period experienced sublethal alterations (Kos et al., 2017), and the midgut cells of bee workers exhibited adverse effects on their cellular structure and histology when sub-lethal dosages of Lead Oxide (PbO) nanoparticles were introduced to sugar syrup (Dabour et al., 2019).

(García-Gómez et al., 2019) indicated that the growth and reproduction of earthworms (*Eisenia Andrei*) were more negatively impacted by the combination of zinc oxide and chlorpyrifos than by using each compound alone.

Silkworm larvae are not affected by AgNPs at low doses (400 mg/L). On the other hand, the larvae showed a decreased moth rate and started to die when treated with 800 mg/L AgNPs. Elevated levels of AgNPs (≥ 800 mg/L) resulted in larval mortality (Meng et al., 2017).

In order to protect parasitoids, predators, and pollinators, it is crucial to understand how nanomaterials affect development, parasitism or predatory efficiency, emergence capacity, and the ability to preserve beneficial insects (Kannan et al., 2020).

14.7 Conclusion

Agriculture and nanotechnology are two-edged swords that present both opportunities and risks. Nanoparticles are toxic not only to crops but also to soil, water, beneficial insects and microorganisms. Furthermore, the toxicity of nanoparticles is influenced by various factors such as dosage, dispersing media type, administration technique, and environmental exposure.

Researches demonstrated that the nanoparticles can readily pass through the membranes of plant cells. As a result, they can hinder photosynthesis and disrupt the regular physiological, biochemical, and molecular processes of a cell. The toxicity of nanoparticles in plants may be caused by a variety of mechanisms, including increased antioxidants, oxidative stress, damage to DNA and lipids, disruption of phytohormone signaling, alterations in signal transduction, and changes in primary and secondary metabolism. In the end, these procedures can cause the plant's defenses to fail. Moreover, nanoparticles may trigger stomatal closure due to their propensity to agglomerate.

Artificial nanoparticle distribution in soils alters aggregate size, transport, suspension stability, and bioavailability. Nanoparticles change their behavior, increase lethality, and intensify soil dangers as they aggregate to a bulk size. Furthermore, dissolved organic matter can coat nanoparticles, changing their surface properties such as pore size distribution, specific surface area, sorption capabilities to organic contaminants, aggregation state, and hazardous impact mechanisms.

Exposure to synthetic nanoparticles results in a significant change in the functional variety and abundance of soil microbial communities. Plant growth-promoting rhizobacteria (PGPR), along with soil nitrogen cycle bacteria like nitrifying and denitrifying bacteria, have exhibited varying levels of inhibition when exposed to engineered nanoparticles (ENPs). Plant-fungi and plant-bacteria interactions were negatively affected by the use of metal-based synthetic nanomaterials. Surface water-waste water treatment can have major effects on biodiversity since nanomaterials can kill both targeted and untargeted bacteria, interact with the soil biota, and be absorbed by plants and crops. Non-target insects also suffer from the expanding application of nanopesticides. Nanomaterials can influence the growth, development, adult emergence, and effectiveness of beneficial insects as parasites or predators. The toxicity mechanisms of nano inputs on beneficial insects in agricultural settings include membrane disruption, protein oxidation, genotoxicity, disruption of energy transduction, reactive oxygen species formation, and toxic chemical release.

Thus, the innovation of ecofriendly and biodegradable nanomaterials that may accomplish agricultural objectives with no ecological impact, must be the focus of study. These eco-friendly substitutes are essential for reducing any environmental risks.

References

- Abd El-Azeim, M. M., Sherif, M. A., Hussien, M. S., Tantawy, I. A. A., & Bashandy, S. O. (2020). Impacts of nano- and non-nanofertilizers on potato quality and productivity. *Acta Ecologica Sinica.*, 40(5), 388–397. <https://doi.org/10.1016/j.chnaes.2019.12.007>
- Abdel-Aziz, H. M. M., Hasaneen, M. N. A., & Omer, A. M. (2019). Impact of engineered nanomaterials either alone or loaded with npk on growth and productivity of french bean plants: Seed priming vs foliar application. *South African Journal of Botany.* <https://doi.org/10.1016/j.sajb.2019.07.005>

- Abdelsalam, N. R., Abdel-Megeed, A., Ali, H. M., Salem, M. Z. M., Al-Hayali, M. F. A., & Elshikh, M. S. (2018). Genotoxicity effects of silver nanoparticles on wheat (*triticum aestivum* L.) root tip cells. *Ecotoxicology and Environmental Safety*. <https://doi.org/10.1016/j.ecoenv.2018.02.069>
- Abou-Zeid, L., & Baraka, H. N. (2014). Combating oxidative stress as a hallmark of cancer and aging: Computational modeling and synthesis of phenylene diamine analogs as potential antioxidant. *Saudi Pharmaceutical Journal*. <https://doi.org/10.1016/j.jsps.2013.07.009>
- Adhikari, T., & Dharmarajan, R. (2022). Nanocontaminants in soil: Emerging concerns and risks. *International Journal of Environmental Science and Technology*, 19, 9129–9148. <https://doi.org/10.1007/s13762-021-03481-1>
- Adrees, M., Ali, S., Rizwan, M., Zia-Ur-Rehman, M., Ibrahim, M., Abbas, F., Farid, M., Qayyum, M. F., & Irshad, M. K. (2015). Mechanisms of silicon-mediated alleviation of heavy metal toxicity in plants: A review. *Ecotoxicology and Environmental Safety*. <https://doi.org/10.1016/j.ecoenv.2015.05.011>
- Ali, M. A., Ahmed, T., Wu, W., Hossain, A., Hafeez, R., Islam Masum, M. M., Wang, Y., An, Q., Sun, G., & Li, B. (2020). Advancements in plant and microbe-based synthesis of metallic nanoparticles and their antimicrobial activity against plant pathogens. *Nanomaterials (Basel)*. <https://doi.org/10.3390/nano10061146>
- Antisari, L. V., Laudicina, V. A., Gatti, A., Carbone, S., Badalucco, L., & Vianello, G. (2015). Soil microbial biomass carbon and fatty acid composition of earthworm *lumbricus rubellus* after exposure to engineered nanoparticles. *Biology and Fertility of Soils*. <https://doi.org/10.1007/s00374-014-0972-1>
- Arruda, S. C., Silva, A. L., Galazzi, R. M., Azevedo, R. A., & Arruda, M. A. (2015). Nanoparticles applied to plant science: A review. *Talanta*. <https://doi.org/10.1016/j.talanta.2014.08.050>
- Atha, D. H., Wang, H., Petersen, E. J., Cleveland, D., Holbrook, R. D., Jaruga, P., Dizdaroglu, M., Xing, B., & Nelson, B. C. (2012). Copper oxide nanoparticle mediated DNA damage in terrestrial plant models. *Environmental Science & Technology*. <https://doi.org/10.1021/es202660k>
- Auffan, M., Achouak, W., Rose, J., Roncato, M. A., Chanéac, C., Waite, D. T., Masion, A., Woick, J. C., Wiesner, M. R., & Bottero, J. Y. (2008). Relation between the redox state of iron-based nanoparticles and their cytotoxicity toward *escherichia coli*. *Environmental Science & Technology*. <https://doi.org/10.1021/es800086f>
- Auffan, M., Rose, J., Bottero, J. Y., Lowry, G. V., Jolivet, J. P., & Wiesner, M. R. (2009). Towards a definition of inorganic nanoparticles from an environmental, health and safety perspective. *Nature Nanotechnology*. <https://doi.org/10.1038/nnano.2009.242>
- Azhar, W., Khan, A. R., Salam, A., Ulhassan, Z., Qi, J., Shah, G., Liu, Y., Chunyan, Y., Yang, S., & Gan, Y. (2023). Ethylene accelerates copper oxide nanoparticle-induced toxicity at physiological, biochemical, and ultrastructural levels in rice seedlings. *Environmental Science and Pollution Research International*. <https://doi.org/10.1007/s11356-022-23915-8>
- Benelli, G. (2016). Plant-mediated biosynthesis of nanoparticles as an emerging tool against mosquitoes of medical and veterinary importance: A review. *Parasitology Research*. <https://doi.org/10.1007/s00436-015-4800-9>
- Ben-Moshe, T., Frenk, S., Dror, I., Minz, D., & Berkowitz, B. (2013). Effects of metal oxide nanoparticles on soil properties. *Chemosphere*. <https://doi.org/10.1016/j.chemosphere.2012.09.018>
- Bleecker, A. B., & Kende, H. (2000). Ethylene: A gaseous signal molecule in plants. *Annual Review of Cell and Developmental Biology*. <https://doi.org/10.1146/annurev.cellbio.16.1.1>
- Boots, B., Russell, C. W., & Green, D. S. (2019). Effects of microplastics in soil ecosystems: Above and below ground. *Environmental Science & Technology*. <https://doi.org/10.1021/acs.est.9b03304>
- Borsuk, G., Paleolog, J., Olszewski, K., & Strachecka, A. (2013). Laboratory assessment of the effect of nanosilver on longevity, sugar syrup ingestion, and infection of honeybees with *nosema* spp. *Medycyna Weterynaryjna*, 69(12), 730–732.

- Bosker, T., Bouwman, L. J., Brun, N. R., Behrens, P., & Vijver, M. G. (2019). Microplastics accumulate on pores in seed capsule and delay germination and root growth of the terrestrial vascular plant *lepidium sativum*. *Chemosphere*. <https://doi.org/10.1016/j.chemosphere.2019.03.163>
- Brausch, K. A., Anderson, T. A., Smith, P. N., & Maul, J. D. (2011). The effect of fullerenes and functionalized fullerenes on daphnia magna phototaxis and swimming behavior. *Environmental Toxicology and Chemistry*. <https://doi.org/10.1002/etc.442>
- Brayner, R., Dahoumane, S. A., Yéprémian, C., Djediat, C., Meyer, M., Couté, A., & Fiévet, F. (2010). Zn nanoparticles: Synthesis, characterization, and ecotoxicological studies. *Langmuir*. <https://doi.org/10.1021/la100293s>
- Canesi, L., Ciacci, C., Fabbri, R., Marcomini, A., Pojana, G., & Gallo, G. (2012). Bivalve molluscs as a unique target group for nanoparticle toxicity. *Marine Environmental Research*. <https://doi.org/10.1016/j.marenvres.2011.06.005>
- Capinera, J. L. (2005). Relationships between insect pests and weeds: An evolutionary perspective. *Weed Science*, 53, 892–901.
- Chai, H., Yao, J., Sun, J., Zhang, C., Liu, W., Zhu, M., & Ceccanti, B. (2015). The effect of metal oxide nanoparticles on functional bacteria and metabolic profiles in agricultural soil. *Bulletin of Environmental Contamination and Toxicology*. <https://doi.org/10.1007/s00128-015-1485-9>
- Chen, J., Liu, B., Yang, Z., Qu, J., Xun, H., Dou, R., Gao, X., & Wang, L. (2018). Phenotypic, transcriptional, physiological and metabolic responses to carbon nanodot exposure in *arabidopsis thaliana* (L.). *Environmental Science: Nano*, 5, 2672–2685.
- Chen, X., Wang, J., You, Y., Wang, R., Chu, S., Chi, Y., Hayat, K., Hui, N., Liu, X., Zhang, D., & Zhou, P. (2022). When nanoparticle and microbes meet: The effect of multi-walled carbon nanotubes on microbial community and nutrient cycling in hyperaccumulator system. *Journal of Hazardous Materials*. <https://doi.org/10.1016/j.jhazmat.2021.126947>
- Chung, I.-M., Rekha, K., Venkidasamy, B., & Thiruvengadam, M. (2019). Effect of copper oxide nanoparticles on the physiology, bioactive molecules, and transcriptional changes in *brassica rapa* ssp. *Rapa* seedlings. *Water, Air, and Soil Pollution*. <https://doi.org/10.1007/s11270-019-4084-2>
- Czarnocka, W., & Karpiński, S. (2018). Friend or foe? Reactive oxygen species production, scavenging and signaling in plant response to environmental stresses. *Free Radical Biology & Medicine*. <https://doi.org/10.1016/j.freeradbiomed.2018.01.011>
- Dabour, K., Al Naggar, Y., Masry, S., Naiem, E., & Giesy, J. P. (2019). Cellular alterations in midgut cells of honey bee workers (*apis millefera* L.) exposed to sublethal concentrations of cdo or pbo nanoparticles or their binary mixture. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2018.09.311>
- Das, R., Leo, B. F., & Murphy, F. (2018). The toxic truth about carbon nanotubes in water purification: A perspective view. *Nanoscale Research Letters*. <https://doi.org/10.1186/s11671-018-2589-z>
- De La Torre-Roche, R., Hawthorne, J., Deng, Y., Xing, B., Cai, W., Newman, L. A., Wang, Q., Ma, X., Hamdi, H., & White, J. C. (2013). Multiwalled carbon nanotubes and c60 fullerenes differentially impact the accumulation of weathered pesticides in four agricultural plants. *Environmental Science & Technology*. <https://doi.org/10.1021/es4034809>
- de Oliveira, J. L., Campos, E. V., Gonçalves da Silva, C. M., Pasquoto, T., Lima, R., & Fraceto, L. F. (2015). Solid lipid nanoparticles co-loaded with simazine and atrazine: Preparation, characterization, and evaluation of herbicidal activity. *Journal of Agricultural and Food Chemistry*. <https://doi.org/10.1021/jf5059045>
- Delay, M., & Frimmel, F. H. (2012). Nanoparticles in aquatic systems. *Analytical and Bioanalytical Chemistry*. <https://doi.org/10.1007/s00216-011-5443-z>
- El-Kalliny, A. S., Abdel-Wahed, M. S., El-Zahhar, A. A., Hamza, I. A., & Gad-Allah, T. A. (2023). Nanomaterials: A review of emerging contaminants with potential health or environmental impact. *Discover Nano*. <https://doi.org/10.1186/s11671-023-03787-8>

- Faisal, M., Saquib, Q., Alatar, A. A., Al-Khedhairi, A. A., Ahmed, M., Ansari, S. M., Alwathnani, H. A., Dwivedi, S., Musarrat, J., & Praveen, S. (2016). Cobalt oxide nanoparticles aggravate DNA damage and cell death in eggplant via mitochondrial swelling and no signaling pathway. *Biological Research*. <https://doi.org/10.1186/s40659-016-0080-9>
- Fang, J., Shan, X. Q., Wen, B., Lin, J. M., & Owens, G. (2009). Stability of titania nanoparticles in soil suspensions and transport in saturated homogeneous soil columns. *Environmental Pollution*. <https://doi.org/10.1016/j.envpol.2008.11.006>
- Fedorenko, A. G., Minkina, T. M., Chernikova, N. P., Fedorenko, G. M., Mandzhieva, S. S., Rajput, V. D., Burachevskaya, M. V., Chaplygin, V. A., Bauer, T. V., Sushkova, S. N., & Soldatov, A. V. (2021). The toxic effect of CuO of different dispersion degrees on the structure and ultrastructure of spring barley cells (*hordeum sativum distichum*). *Environmental Geochemistry and Health*. <https://doi.org/10.1007/s10653-020-00530-5>
- Fellmann, S., & Eichert, T. (2017). Acute effects of engineered nanoparticles on the growth and gas exchange of Zea mays L.—What are the underlying causes? *Water, Air, & Soil Pollution*. <https://doi.org/10.1007/s11270-017-3364-y>
- Gangwar, S., Singh, V. P., Tripathi, D. K., Chauhan, D. K., Prasad, S. M., & Maurya, J. N. (2014). Chapter 10 – plant responses to metal stress: The emerging role of plant growth hormones in toxicity alleviation. In P. Ahmad & S. Rasool (Eds.), *Emerging technologies and management of crop stress tolerance* (pp. 215–248). Academic.
- Gao, F., Liu, C., Qu, C., Zheng, L., Yang, F., Su, M., & Hong, F. (2008). Was improvement of spinach growth by nano-tiO₂ treatment related to the changes of rubisco activase? *Biometals*. <https://doi.org/10.1007/s10534-007-9110-y>
- Gao, M., Chang, J., Wang, Z., Zhang, H., & Wang, T. (2023). Advances in transport and toxicity of nanoparticles in plants. *Journal of Nanobiotechnology*. <https://doi.org/10.1186/s12951-023-01830-5>
- García-Gómez, C., Babín, M., García, S., Almendros, P., Pérez, R. A., & Fernández, M. D. (2019). Joint effects of zinc oxide nanoparticles and chlorpyrifos on the reproduction and cellular stress responses of the earthworm *Eisenia andrei*. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2019.06.083>
- Gehrke, I., Geiser, A., & Somborn-Schulz, A. (2015). Innovations in nanotechnology for water treatment. *Nanotechnology, Science and Applications*. <https://doi.org/10.2147/nsa.S43773>
- Ghosh, M., Jana, A., Sinha, S., Jothiramajayam, M., Nag, A., Chakraborty, A., Mukherjee, A., & Mukherjee, A. (2016). Effects of ZnO nanoparticles in plants: Cytotoxicity, genotoxicity, deregulation of antioxidant defenses, and cell-cycle arrest. *Mutation Research, Genetic Toxicology and Environmental Mutagenesis*. <https://doi.org/10.1016/j.mrgentox.2016.07.006>
- Glavan, G., Milivojević, T., Božić, J., Sepčić, K., & Drobne, D. (2017). Feeding preference and sub-chronic effects of ZnO nanomaterials in honey bees (*Apis mellifera carnica*). *Archives of Environmental Contamination and Toxicology*. <https://doi.org/10.1007/s00244-017-0385-x>
- Gupta, R., & Xie, H. (2018). Nanoparticles in daily life: Applications, toxicity and regulations. *Journal of Environmental Pathology, Toxicology and Oncology*. <https://doi.org/10.1615/JEnvironPatholToxicolOncol.2018026009>
- Hao, Y., Yu, F., Lv, R., Ma, C., Zhang, Z., Rui, Y., Liu, L., Cao, W., & Xing, B. (2016). Carbon nanotubes filled with different ferromagnetic alloys affect the growth and development of rice seedlings by changing the C:N ratio and plant hormones concentrations. *PLoS One*. <https://doi.org/10.1371/journal.pone.0157264>
- He, S., Feng, Y., Ren, H., Zhang, Y., Gu, N., & Lin, X. (2011). The impact of iron oxide magnetic nanoparticles on the soil bacterial community. *Journal of Soils and Sediments*. <https://doi.org/10.1007/s11368-011-0415-7>
- Hossain, Z., Mustafa, G., & Komatsu, S. (2015). Plant responses to nanoparticle stress. *International Journal of Molecular Sciences*. <https://doi.org/10.3390/ijms161125980>
- Jalil, R., & Yousef, A. (2015). Comparison the phytotoxicity of TiO₂ nanoparticles with bulk particles on amber 33 variety of rice (*Oryza sativa*) in vitro. *Scholarly Academic Journal of Bioscience*, 3(3), 254–262.

- Jan, N., Majeed, N., Ahmad, M., Ahmad Lone, W., & John, R. (2022). Nano-pollution: Why it should worry us. *Chemosphere*. <https://doi.org/10.1016/j.chemosphere.2022.134746>
- Janvier, C., Villeneuve, F., Alabouvette, C., Edel-Hermann, V., Mateille, T., & Steinberg, C. (2007). Soil health through soil disease suppression: Which strategy from descriptors to indicators? *Soil Biology and Biochemistry*. <https://doi.org/10.1016/j.soilbio.2006.07.001>
- Jiang, X., Miclăuş, T., Wang, L., Foldbjerg, R., Sutherland, D. S., Autrup, H., Chen, C., & Beer, C. (2015). Fast intracellular dissolution and persistent cellular uptake of silver nanoparticles in cho-k1 cells: Implication for cytotoxicity. *Nanotoxicology*. <https://doi.org/10.3109/17435390.2014.907457>
- Jogaiah, S., Paidi, M. K., Venugopal, K., Geetha, N., Mujtaba, M., Udikeri, S. S., & Govarthanam, M. (2021). Phytotoxicological effects of engineered nanoparticles: An emerging nanotoxicology. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2021.149809>
- Joner, E., Hartnik, T., & Amundsen, C. (2008). Norwegian pollution control authority report no. *Talanta*.
- Joško, I., Oleszczuk, P., & Futa, B. (2014). The effect of inorganic nanoparticles (zno, cr2o3, cuo and ni) and their bulk counterparts on enzyme activities in different soils. *Geoderma*. <https://doi.org/10.1016/j.geoderma.2014.06.012>
- Kalaji, H. M., Schansker, G., Ladle, R. J., Goltsev, V., Bosa, K., Allakhverdiev, S. I., Brestic, M., Bussotti, F., Calatayud, A., Dąbrowski, P., Elsheery, N. I., Ferroni, L., Guidi, L., Hogewoning, S. W., Jajoo, A., Misra, A. N., Nebauer, S. G., Pancaldi, S., Penella, C., Poli, D., Pollastrini, M., Romanowska-Duda, Z. B., Rutkowska, B., Seródio, J., Suresh, K., Szulc, W., Tambussi, E., Yannicari, M., & Zivcak, M. (2014). Frequently asked questions about in vivo chlorophyll fluorescence: Practical issues. *Photosynthesis Research*. <https://doi.org/10.1007/s11120-014-0024-6>
- Kalman, J., Paul, K. B., Khan, F. R., Stone, V., & Fernandes, T. F. (2015). Characterisation of bioaccumulation dynamics of three differently coated silver nanoparticles and aqueous silver in a simple freshwater food chain. *Environmental Chemistry*, 12, 662–672.
- Kanerva, T., Palojarvi, A., Rämö, K., & Manninen, S. (2008). Changes in soil microbial community structure under elevated tropospheric o3 and co2. *Soil Biology and Biochemistry*. <https://doi.org/10.1016/j.soilbio.2008.06.007>
- Kannan, M., & Elango, K. (2019). Effect of silica nano particles to egg parasitoids. *Trichogramma chilonis*.
- Kannan, M., Elango, K., Tamilnayagan, T., Preetha, S., & Kasivelu, G. (2020). Impact of nanomaterials on beneficial insects in agricultural ecosystems. In D. Thangadurai, J. Sangeetha, & R. Prasad (Eds.), *Nanotechnology for food, agriculture, and environment* (pp. 379–393). Springer International Publishing.
- Karami Mehrian, S., & De Lima, R. (2016). Nanoparticles cyto and genotoxicity in plants: Mechanisms and abnormalities. *Environmental Nanotechnology, Monitoring & Management*. <https://doi.org/10.1016/j.enmm.2016.08.003>
- Kasemets, K., Ivask, A., Dubourguier, H. C., & Kahru, A. (2009). Toxicity of nanoparticles of zno, cuo and tio2 to yeast saccharomyces cerevisiae. *Toxicology In Vitro*. <https://doi.org/10.1016/j.tiv.2009.05.015>
- Keller, A. A., Huang, Y., & Nelson, J. (2018). Detection of nanoparticles in edible plant tissues exposed to nano-copper using single-particle icp-ms. *Journal of Nanoparticle Research*. <https://doi.org/10.1007/s11051-018-4192-8>
- Khan, M., Khan, M. S. A., Borah, K. K., Goswami, Y., Hakeem, K. R., & Chakrabarty, I. (2021). The potential exposure and hazards of metal-based nanoparticles on plants and environment, with special emphasis on zno nps, tio2 nps, and agnps: A review. *Environmental Advances*. <https://doi.org/10.1016/j.envadv.2021.100128>
- Khanna, K., Kohli, S. K., Handa, N., Kaur, H., Ohri, P., Bhardwaj, R., Yousaf, B., Rinklebe, J., & Ahmad, P. (2021). Enthraling the impact of engineered nanoparticles on soil microbiome: A concentric approach towards environmental risks and cogitation. *Ecotoxicology and Environmental Safety*. <https://doi.org/10.1016/j.ecoenv.2021.112459>

- Kim, S., Sin, H., Lee, S., & Lee, I. (2013). Influence of metal oxide particles on soil enzyme activity and bioaccumulation of two plants. *Journal of Microbiology and Biotechnology*. <https://doi.org/10.4014/jmb.1304.04084>
- Klaine, S. J., Alvarez, P. J., Batley, G. E., Fernandes, T. F., Handy, R. D., Lyon, D. Y., Mahendra, S., McLaughlin, M. J., & Lead, J. R. (2008). Nanomaterials in the environment: Behavior, fate, bioavailability, and effects. *Environmental Toxicology and Chemistry*. <https://doi.org/10.1897/08-090.1>
- Kos, M., Kokalj, A. J., Glavan, G., Marolt, G., Zidar, P., Božič, J., Novak, S., & Drobne, D. (2017). Cerium (iv) oxide nanoparticles induce sublethal changes in honeybees after chronic exposure. *Environmental Science: Nano.*, 4, 2297–2310.
- Kumar, N., Shah, V., & Walker, V. K. (2012). Influence of a nanoparticle mixture on an arctic soil community. *Environmental Toxicology and Chemistry*. <https://doi.org/10.1002/etc.721>
- Kumari, J., Kumar, D., Mathur, A., Naseer, A., Kumar, R. R., Thanjavur Chandrasekaran, P., Chaudhuri, G., Pulimi, M., Raichur, A. M., Babu, S., Chandrasekaran, N., Nagarajan, R., & Mukherjee, A. (2014). Cytotoxicity of tio2 nanoparticles towards freshwater sediment micro-organisms at low exposure concentrations. *Environmental Research*. <https://doi.org/10.1016/j.envres.2014.09.025>
- Kumari, R., Suman, K., Karmakar, S., Mishra, V., Lakra, S. G., Saurav, G. K., & Mahto, B. K. (2023). Regulation and safety measures for nanotechnology-based Agri-products. *Frontiers in Genome Editing*. <https://doi.org/10.3389/fgeed.2023.1200987>
- Lekamge, S., Ball, A. S., Shukla, R., & Nugegoda, D. (2020). The toxicity of nanoparticles to organisms in freshwater. *Reviews of Environmental Contamination and Toxicology*. https://doi.org/10.1007/398_2018_18
- Li, F., Gu, Z., Wang, B., Xie, Y., Ma, L., Xu, K., Ni, M., Zhang, H., Shen, W., & Li, B. (2014). Effects of the biosynthesis and signaling pathway of ecdysterone on silkworm (bombyx mori) following exposure to titanium dioxide nanoparticles. *Journal of Chemical Ecology*. <https://doi.org/10.1007/s10886-014-0487-0>
- Li, S., Ma, H., Wallis, L. K., Etterson, M. A., Riley, B., Hoff, D. J., & Diamond, S. A. (2016). Impact of natural organic matter on particle behavior and phototoxicity of titanium dioxide nanoparticles. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2015.09.141>
- Lian, J., Wu, J., Xiong, H., Zeb, A., Yang, T., Su, X., Su, L., & Liu, W. (2020). Impact of polystyrene nanoplastics (psnps) on seed germination and seedling growth of wheat (triticum aestivum l.). *Journal of Hazardous Materials*. <https://doi.org/10.1016/j.jhazmat.2019.121620>
- Lin, D., & Xing, B. (2007). Phytotoxicity of nanoparticles: Inhibition of seed germination and root growth. *Environmental Pollution*. <https://doi.org/10.1016/j.envpol.2007.01.016>
- Liu, Y., Xu, K., & Cheng, J. (2020). Different nanomaterials for soil remediation affect avoidance response and toxicity response in earthworm (eisenia fetida). *Bulletin of Environmental Contamination and Toxicology*. <https://doi.org/10.1007/s00128-020-02823-y>
- Maity, S., Chatterjee, A., Guchhait, R., De, S., & Pramanick, K. (2020). Cytogenotoxic potential of a hazardous material, polystyrene microparticles on allium cepa l. *Journal of Hazardous Materials*. <https://doi.org/10.1016/j.jhazmat.2019.121560>
- Malakar, A., & Snow, D. D. (2020). Chapter 17 – nanoparticles as sources of inorganic water pollutants. In P. Devi, P. Singh, & S. K. Kansal (Eds.), *Inorganic pollutants in water* (pp. 337–370). Elsevier.
- Marslin, G., Sheeba, C. J., & Franklin, G. (2017). Nanoparticles alter secondary metabolism in plants via ros burst. *Frontiers in Plant Science*. <https://doi.org/10.3389/fpls.2017.00832>
- McKee, M. S., & Filser, J. (2016). Impacts of metal-based engineered nanomaterials on soil communities. *Environmental Science: Nano.*, 3, 506–533.
- Medina-Pérez, G., Fernández-Luqueño, F., Vazquez-Núñez, E., López-Valdez, F., Prieto-Mendez, J., Madariaga-Navarrete, A., & Miranda-Arámbula, M. (2019). Remediating polluted soils using nanotechnologies: Environmental benefits and risks. *Polish Journal of Environmental Studies.*, 28, 1013–1030.

- Meng, X., Abdli, N., Wang, N., Lü, P., Nie, Z., Dong, X., Lu, S., & Chen, K. (2017). Effects of ag nanoparticles on growth and fat body proteins in silkworms (*bombyx mori*). *Biological Trace Element Research*. <https://doi.org/10.1007/s12011-017-1001-7>
- Milivojević, T., Glavan, G., Božić, J., Sepčić, K., Mesarić, T., & Drobne, D. (2015). Neurotoxic potential of ingested zn nanomaterials on bees. *Chemosphere*. <https://doi.org/10.1016/j.chemosphere.2014.07.054>
- Mirzajani, F., Askari, H., Hamzelou, S., Farzaneh, M., Ghassempour, A., 2013. Effect of silver nanoparticles on oryza sativa l. And its rhizosphere bacteria. *Ecotoxicology and Environmental Safety* doi:<https://doi.org/10.1016/j.ecoenv.2012.10.018>.
- Mishra, M. (2019). Effect of accumulation of nanoparticles in soil health-a concern on future. *Frontiers in Nanoscience and Nanotechnology*, 5(1), 1–9.
- Mishra, S., Singh, A., Keswani, C., & Singh, H. (2014). Nanotechnology: Exploring potential application in agriculture and its opportunities and constraints. *Biotech today.*, 4, 9–14.
- Moazzami Farida, S. H., Karamian, R., & Albrectsen, B. R. (2020). Silver nanoparticle pollutants activate oxidative stress responses and rosmarinic acid accumulation in sage. *Physiologia Plantarum*. <https://doi.org/10.1111/ppl.13172>
- Mondal, A., Basu, R., Das, S., & Nandy, P. (2011). Beneficial role of carbon nanotubes on mustard plant growth: An agricultural prospect. *Journal of Nanoparticle Research*. <https://doi.org/10.1007/s11051-011-0406-z>
- More, P. R., Pandit, S., Filippis, A., Franci, G., Mijakovic, I., & Galdiero, M. (2023). Silver nanoparticles: Bactericidal and mechanistic approach against drug resistant pathogens. *Microorganisms*. <https://doi.org/10.3390/microorganisms11020369>
- Mortimer, M., Kasemets, K., & Kahru, A. (2010). Toxicity of zn and cuo nanoparticles to ciliated protozoa tetrahymena thermophila. *Toxicology*. <https://doi.org/10.1016/j.tox.2009.07.007>
- Mullineaux, P. M., Exposito-Rodriguez, M., Laissue, P. P., & Smirnov, N. (2018). Ros-dependent signalling pathways in plants and algae exposed to high light: Comparisons with other eukaryotes. *Free Radical Biology & Medicine*. <https://doi.org/10.1016/j.freeradbiomed.2018.01.033>
- Mura, S., Seddaiu, G., Bacchini, F., Roggero, P. P., & Greppi, G. F. (2013). Advances of nanotechnology in agro-environmental studies. *Italian Journal of Agronomy*, 8, e18.
- Mushtaq, W., Shakeel, A., Fazili, M. A., Chakrabarty, I., & Sevidik, M. (2020). Pros and cons of nanotechnology. In *Nanobiotechnology in agriculture: An approach towards sustainability* (pp. 207–222).
- Muzammil, S., Ashraf, A., Siddique, M. H., Aslam, B., Rasul, I., Abbas, R., Afzal, M., Faisal, M., & Hayat, S. (2023). A review on toxicity of nanomaterials in agriculture: Current scenario and future prospects. *Science Progress*. <https://doi.org/10.1177/00368504231221672>
- Nair, P. M. G., & Chung, I. M. (2017). Regulation of morphological, molecular and nutrient status in arabidopsis thaliana seedlings in response to zn nanoparticles and zn ion exposure. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2016.10.017>
- Navarro, E., Baun, A., Behra, R., Hartmann, N. B., Filser, J., Miao, A. J., Quigg, A., Santschi, P. H., & Sigg, L. (2008). Environmental behavior and ecotoxicity of engineered nanoparticles to algae, plants, and fungi. *Ecotoxicology*. <https://doi.org/10.1007/s10646-008-0214-0>
- Nhan le, V., Ma, C., Rui, Y., Liu, S., Li, X., Xing, B., & Liu, L. (2015). Phytotoxic mechanism of nanoparticles: Destruction of chloroplasts and vascular bundles and alteration of nutrient absorption. *Scientific Reports*. <https://doi.org/10.1038/srep11618>
- Nowack, B., Ranville, J. F., Diamond, S., Gallego-Urrea, J. A., Metcalfe, C., Rose, J., Horne, N., Koelmans, A. A., & Klaine, S. J. (2012). Potential scenarios for nanomaterial release and subsequent alteration in the environment. *Environmental Toxicology and Chemistry*. <https://doi.org/10.1002/etc.726>
- O'Brien, J. A., & Benková, E. (2013). Cytokinin cross-talking during biotic and abiotic stress responses. *Frontiers in Plant Science*. <https://doi.org/10.3389/fpls.2013.00451>
- Ouyang, S., Li, Y., Zheng, T., Wu, K., Wang, X., & Zhou, Q. (2022). Ecotoxicity of natural nanocolloids in aquatic environment. *Journal*. <https://doi.org/10.3390/w14192971>

- Özkan, Y., Irende, İ., Akdeniz, G., Kabakçı, D., & Sökmen, M. (2014). Evaluation of the comparative acute toxic effects of tio₂, ag-tio₂ and zn-tio₂ composite nanoparticles on honey bee (*apis mellifera*). *Journal of International Environmental Application & Science*, 10(1), 26–36.
- Paranjpe, M., Neuhaus, V., Finke, J. H., Richter, C., Gothsch, T., Kwade, A., Büttgenbach, S., Braun, A., & Müller-Goymann, C. C. (2013). In vitro and ex vivo toxicological testing of sildenafil-loaded solid lipid nanoparticles. *Inhalation Toxicology*. <https://doi.org/10.3109/08958378.2013.810315>
- Patlolla, A. K., Berry, A., May, L., & Tchounwou, P. B. (2012). Genotoxicity of silver nanoparticles in vicia faba: A pilot study on the environmental monitoring of nanoparticles. *International Journal of Environmental Research and Public Health*. <https://doi.org/10.3390/ijerph9051649>
- Perreault, F., Samadani, M., & Dewez, D. (2014). Effect of soluble copper released from copper oxide nanoparticles solubilisation on growth and photosynthetic processes of *lemna gibba* L. *Nanotoxicology*. <https://doi.org/10.3109/17435390.2013.789936>
- Petosa, A. R., Jaisi, D. P., Quevedo, I. R., Elimelech, M., & Tufenkji, N. (2010). Aggregation and deposition of engineered nanomaterials in aquatic environments: Role of physicochemical interactions. *Environmental Science & Technology*. <https://doi.org/10.1021/es100598h>
- Phenrat, T., Long, T. C., Lowry, G. V., & Veronesi, B. (2009). Partial oxidation (“aging”) and surface modification decrease the toxicity of nanosized zerovalent iron. *Environmental Science & Technology*. <https://doi.org/10.1021/es801955n>
- Philippe, A., & Schaumann, G. E. (2014). Interactions of dissolved organic matter with natural and engineered inorganic colloids: A review. *Environmental Science & Technology*. <https://doi.org/10.1021/es502342r>
- Pokhrel, L. R., & Dubey, B. (2012). Potential impact of low-concentration silver nanoparticles on predator-prey interactions between predatory dragonfly nymphs and *daphnia magna* as a prey. *Environmental Science & Technology*. <https://doi.org/10.1021/es204055c>
- Pui, D. Y. H., Chen, S.-C., & Zuo, Z. (2014). Pm_{2.5} in China: Measurements, sources, visibility and health effects, and mitigation. *Particuology*. <https://doi.org/10.1016/j.partic.2013.11.001>
- Qamer, Z., Chaudhary, M. T., Du, X., Hinze, L., & Azhar, M. T. (2021). Review of oxidative stress and antioxidative defense mechanisms in *gossypium hirsutum* L. in response to extreme abiotic conditions. *Journal of Cotton Research*. <https://doi.org/10.1186/s42397-021-00086-4>
- Rai, M., Kon, K., Ingle, A., Duran, N., Galdiero, S., & Galdiero, M. (2014). Broad-spectrum bioactivities of silver nanoparticles: The emerging trends and future prospects. *Applied Microbiology and Biotechnology*. <https://doi.org/10.1007/s00253-013-5473-x>
- Rajput, V., Minkina, T., Mazarji, M., Shende, S., Sushkova, S., Mandzhieva, S., Burachevskaya, M., Chaplygin, V., Singh, A., & Jatav, H. (2020). Accumulation of nanoparticles in the soil-plant systems and their effects on human health. *Annals of Agricultural Sciences*. <https://doi.org/10.1016/j.aosas.2020.08.001>
- Raliya, R., Franke, C., Chavalmane, S., Nair, R., Reed, N., & Biswas, P. (2016). Quantitative understanding of nanoparticle uptake in watermelon plants. *Frontiers in Plant Science*. <https://doi.org/10.3389/fpls.2016.01288>
- Rashid, M. I., Shahzad, T., Shahid, M., Ismail, I. M., Shah, G. M., & Almeelbi, T. (2017). Zinc oxide nanoparticles affect carbon and nitrogen mineralization of phoenix *dactylifera* leaf litter in a sandy soil. *Journal of Hazardous Materials*. <https://doi.org/10.1016/j.jhazmat.2016.10.063>
- Rico, C. M., Hong, J., Morales, M. I., Zhao, L., Barrios, A. C., Zhang, J. Y., Peralta-Videa, J. R., & Gardea-Torresdey, J. L. (2013). Effect of cerium oxide nanoparticles on rice: A study involving the antioxidant defense system and in vivo fluorescence imaging. *Environmental Science & Technology*. <https://doi.org/10.1021/es401032m>
- Rodrigues, D. F., Jaisi, D. P., & Elimelech, M. (2013). Toxicity of functionalized single-walled carbon nanotubes on soil microbial communities: Implications for nutrient cycling in soil. *Environmental Science & Technology*. <https://doi.org/10.1021/es304002q>

- Sadhu, A., Ghosh, I., Moriyasu, Y., Mukherjee, A., & Bandyopadhyay, M. (2018). Role of cerium oxide nanoparticle-induced autophagy as a safeguard to exogenous H_2O_2 -mediated DNA damage in tobacco BY-2 cells. *Mutagenesis*. <https://doi.org/10.1093/mutage/gy004>
- Sadžak, A., Mravljak, J., Maltar-Strečević, N., Arsov, Z., Baranović, G., Erceg, I., Kriechbaum, M., Strasser, V., Přibyl, J., & Šegota, S. (2020). The structural integrity of the model lipid membrane during induced lipid peroxidation: The role of flavonols in the inhibition of lipid peroxidation. *Antioxidants (Basel)*. <https://doi.org/10.3390/antiox9050430>
- Saliba, A. M., de Assis, M. C., Nishi, R., Raymond, B., Marques Ede, A., Lopes, U. G., Touqui, L., & Plotkowski, M. C. (2006). Implications of oxidative stress in the cytotoxicity of *Pseudomonas aeruginosa* exou. *Microbes and Infection*. <https://doi.org/10.1016/j.micinf.2005.07.011>
- Santiago-Martín, A.d., Constantin, B., Guesdon, G., Kagambega, N., Raymond, S., & Cloutier, R. G. (2016). Bioavailability of engineered nanoparticles in soil systems. *Toxic, and Radioactive Waste*, 20(1). [https://doi.org/10.1061/\(ASCE\)HZ.2153-5515.0000263](https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000263)
- Saqib, Q., Faisal, M., Alatar, A. A., Al-Khedhairi, A. A., Ahmed, M., Ansari, S. M., Alwathnani, H. A., Okla, M. K., Dwivedi, S., Musarrat, J., Praveen, S., Khan, S. T., Wahab, R., Siddiqui, M. A., & Ahmad, J. (2016). Genotoxicity of ferric oxide nanoparticles in *Raphanus sativus*: Deciphering the role of signaling factors, oxidative stress and cell death. *Journal of Environmental Sciences (China)*. <https://doi.org/10.1016/j.jes.2015.12.037>
- Sharma, V. K., Filip, J., Zboril, R., & Varma, R. S. (2015). Natural inorganic nanoparticles--formation, fate, and toxicity in the environment. *Chemical Society Reviews*. <https://doi.org/10.1039/c5cs00236b>
- Shaw, A. K., & Hossain, Z. (2013). Impact of nano-cuO stress on rice (*Oryza sativa* L.) seedlings. *Chemosphere*. <https://doi.org/10.1016/j.chemosphere.2013.05.044>
- Singh, D., Sharma, A., Verma, S. K., Pandey, H., & Pandey, M. (2024). Impact of nanoparticles on plant physiology, nutrition, and toxicity: A short review. *Next Nanotechnology*. <https://doi.org/10.1016/j.nxnano.2024.100081>
- Snousy, M. G., Helmy, H. M., Wu, J., Zawrah, M. F., & Abouelmagd, A. (2023). Nanotechnology for water treatment: Is it the best solution now? *Journal of Earth Science*. <https://doi.org/10.1007/s12583-023-1928-8>
- Speranza, A., Leopold, K., Maier, M., Taddei, A. R., & Scoccianti, V. (2010). Pd-nanoparticles cause increased toxicity to kiwifruit pollen compared to soluble Pd(II). *Environmental Pollution*. <https://doi.org/10.1016/j.envpol.2009.09.022>
- Stone, V., Nowack, B., Baun, A., van den Brink, N., Kammer, F., Dusinska, M., Handy, R., Hankin, S., Hassellöv, M., Joner, E., & Fernandes, T. F. (2010). Nanomaterials for environmental studies: Classification, reference material issues, and strategies for physico-chemical characterisation. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2009.10.035>
- Sturikova, H., Krystofova, O., Huska, D., & Adam, V. (2018). Zinc, zinc nanoparticles and plants. *Journal of Hazardous Materials*. <https://doi.org/10.1016/j.jhazmat.2018.01.040>
- Sun, X. D., Yuan, X. Z., Jia, Y., Feng, L. J., Zhu, F. P., Dong, S. S., Liu, J., Kong, X., Tian, H., Duan, J. L., Ding, Z., Wang, S. G., & Xing, B. (2020). Differentially charged nanoplastics demonstrate distinct accumulation in *Arabidopsis thaliana*. *Nature Nanotechnology*. <https://doi.org/10.1038/s41565-020-0707-4>
- Surendranath, A., & Mohanan, P. V. (2020). Impact of nanoparticles in balancing the ecosystem. *Biointerface Research in Applied Chemistry*, 11(3), 10461–10481.
- Thakur, M. P., Milcu, A., Manning, P., Niklaus, P. A., Roscher, C., Power, S., Reich, P. B., Scheu, S., Tilman, D., Ai, F., Guo, H., Ji, R., Pierce, S., Ramirez, N. G., Richter, A. N., Steinauer, K., Strecker, T., Vogel, A., & Eisenhauer, N. (2015). Plant diversity drives soil microbial biomass carbon in grasslands irrespective of global environmental change factors. *Global Change Biology*. <https://doi.org/10.1111/gcb.13011>
- Thiruvengadam, M., Gurunathan, S., & Chung, I. M. (2015). Physiological, metabolic, and transcriptional effects of biologically-synthesized silver nanoparticles in turnip (*Brassica rapa* ssp. *Rapa* L.). *Protoplasma*. <https://doi.org/10.1007/s00709-014-0738-5>

- Thiruvengadam, M., Chi, H. Y., & Kim, S. H. (2024). Impact of nanopollution on plant growth, photosynthesis, toxicity, and metabolism in the agricultural sector: An updated review. *Plant Physiology and Biochemistry*. <https://doi.org/10.1016/j.plaphy.2024.108370>
- Thul, S. T., & Sarangi, B. K. (2015). Implications of nanotechnology on plant productivity and its rhizospheric environment. In M. H. Siddiqui, M. H. Al-Wahaibi, & F. Mohammad (Eds.), *Nanotechnology and plant sciences: Nanoparticles and their impact on plants* (pp. 37–53). Springer International Publishing.
- Tripathi, D. K., Shweta, Singh, S., Singh, S., Pandey, R., Singh, V. P., Sharma, N. C., Prasad, S. M., Dubey, N. K., & Chauhan, D. K. (2017). An overview on manufactured nanoparticles in plants: Uptake, translocation, accumulation and phytotoxicity. *Plant Physiology and Biochemistry*. <https://doi.org/10.1016/j.plaphy.2016.07.030>
- Tripathi, S., Mahra, S., J. V., Tiwari, K., Rana, S., Tripathi, D. K., Sharma, S., & Sahi, S. (2023). Recent advances and perspectives of nanomaterials in agricultural management and associated environmental risk: A review. *Nanomaterials (Basel)*. <https://doi.org/10.3390/nano13101604>
- Ullah, H., Li, X., Peng, L., Cai, Y., & Mielke, H. W. (2020). In vivo phytotoxicity, uptake, and translocation of pbs nanoparticles in maize (zea mays l.) plants. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2020.139558>
- Vannini, C., Domingo, G., Onelli, E., Prinsi, B., Marsoni, M., Espen, L., & Bracale, M. (2013). Morphological and proteomic responses of eruca sativa exposed to silver nanoparticles or silver nitrate. *PLoS One*. <https://doi.org/10.1371/journal.pone.0068752>
- Vinković, T., Novák, O., Stnad, M., Goessler, W., Jurašin, D. D., Paradiković, N., & Vrček, I. V. (2017). Cytokinin response in pepper plants (capsicum annuum l.) exposed to silver nanoparticles. *Environmental Research*. <https://doi.org/10.1016/j.envres.2017.03.015>
- Wang, Z., Xie, X., Zhao, J., Liu, X., Feng, W., White, J. C., & Xing, B. (2012). Xylem- and phloem-based transport of cuo nanoparticles in maize (zea mays l.). *Environmental Science & Technology*. <https://doi.org/10.1021/es204212z>
- Wang, X., Xie, H., Wang, P., & Yin, H. (2023). Nanoparticles in plants: Uptake, transport and physiological activity in leaf and root. *Materials (Basel)*. <https://doi.org/10.3390/ma16083097>
- Worrall, E. A., Hamid, A., Mody, K. T., Mitter, N., & Pappu, H. R. (2018). Nanotechnology for plant disease management. *Journal*. <https://doi.org/10.3390/agronomy8120285>
- Wu, M.-S., Lin, Y.-P., Lin, C.-H., & Lee, J.-T. (2012). Formation of nano-scaled crevices and spacers in nio-attached graphene oxide nanosheets for supercapacitors. *Journal of Materials Chemistry*, 22, 2442–2448.
- Wu, F., Harper, B. J., & Harper, S. L. (2019). Comparative dissolution, uptake, and toxicity of zinc oxide particles in individual aquatic species and mixed populations. *Environmental Toxicology and Chemistry*. <https://doi.org/10.1002/etc.4349>
- Xiao, Z., Yue, L., Wang, C., Chen, F., Ding, Y., Liu, Y., Cao, X., Chen, Z., Rasmann, S., & Wang, Z. (2021). Downregulation of the photosynthetic machinery and carbon storage signaling pathways mediate la(2)o(3) nanoparticle toxicity on radish taproot formation. *Journal of Hazardous Materials*. <https://doi.org/10.1016/j.jhazmat.2020.124971>
- Yan, A., & Chen, Z. (2019). Impacts of silver nanoparticles on plants: A focus on the phytotoxicity and underlying mechanism. *International Journal of Molecular Sciences*. <https://doi.org/10.3390/ijms20051003>
- Yang, J., Cao, W., & Rui, Y. (2017). Interactions between nanoparticles and plants: Phytotoxicity and defense mechanisms. *Journal of plant interactions*, 12, 158–169.
- Yang, J., Hou, B., Wang, J., Tian, B., Bi, J., Wang, N., Li, X., & Huang, X. (2019). Nanomaterials for the removal of heavy metals from wastewater. *Nanomaterials (Basel)*. <https://doi.org/10.3390/nano9030424>
- Yang, Y., Du, P., Lai, W., Yin, L., Ding, Y., Li, Z., & Hu, H. (2022). Changes in primary metabolites and volatile organic compounds in cotton seedling leaves exposed to silver ions and silver nanoparticles revealed by metabolomic analysis. *PeerJ*. <https://doi.org/10.7717/peerj.13336>

- Yanık, F., & Vardar, F. (2015). Toxic effects of aluminum oxide (Al_2O_3) nanoparticles on root growth and development in *triticum aestivum*. *Water, Air, & Soil Pollution*. <https://doi.org/10.1007/s11270-015-2566-4>
- Zafar, H., Javed, R., & Zia, M. (2023). Nanotoxicity assessment in plants: An updated overview. *Environmental Science and Pollution Research International*. <https://doi.org/10.1007/s11356-023-29150-z>
- Zou, X., Shi, J., & Zhang, H. (2015). Morphological evolution and reconstruction of silver nanoparticles in aquatic environments: The roles of natural organic matter and light irradiation. *Journal of Hazardous Materials*. <https://doi.org/10.1016/j.jhazmat.2015.03.005>
- Zoufan, P., Baroonian, M., & Zargar, B. (2020). Zn nanoparticles-induced oxidative stress in *chenopodium murale* L. Zn uptake, and accumulation under hydroponic culture. *Environmental Science and Pollution Research International*. <https://doi.org/10.1007/s11356-020-07735-2>

Chapter 15

Polymeric Based Nanomaterials: A Promising Approach in Plant Protection and Food Packaging



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Abstract In the past, excessive use of chemical fertilizers and pesticides in agriculture has led to biodiversity loss, environmental contamination, and the establishment of resistance in agricultural pathogens and pests. Nano bio-based materials, namely polymeric ones, have been utilized in crop protection and food packaging due to their size-dependent properties and safe nature. Biopolymer-based nanoparticles have the potential to significantly contribute to promoting plant development, effectively managing pests and diseases, safeguarding against phytopathogens, and so improving food production, food security, and food safety. In addition, polymeric nanoparticles are currently being used in the food sector, regardless of the fact that laws for their use have not been fully defined. This is because any new system, especially in its early stages, is likely to encounter certain difficulties. Nevertheless, ongoing research is anticipated to enhance sensitivity, chemical release, carrier modification, and biocompatibility, hence facilitating improvements in the quality of food products in terms of taste, flavor, texture, and freshness. Currently, there are various efforts underway worldwide to develop the nanoformulations employing biopolymer-based nanomaterials as agrochemicals. This technique aims to protect crop plants from harmful infections in an environmentally acceptable manner. Consequently, the advent of nanotechnology in the food business has led to several alterations in areas like as packaging, preservation, and processing. These modifications have greatly extended the duration for which food may be stored, enhanced the ability to identify early signs of food spoiling, and facilitated effective management practices that permit the prolongation of food freshness and shelf life. Additionally, they can also be utilized to optimize the distribution of food supplies within the supply food chain.

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15.1 Introduction

The US National Nanotechnology Initiative (2018) defines nanotechnology as the scientific study of manipulating and organizing matter at sizes smaller than 100 nm, with an emphasis on controlling, producing, processing, and restructuring matter. Nanotechnology is a burgeoning scientific field that integrates several disciplines like chemistry, physics, biology, and engineering to advance the understanding, creation, and control of novel nanostructures or nanomaterials. These for use in the food industry. The success of an innovative product is linked to the innovation that was utilized in its creation (O'Callaghan & Kerry, 2016). Nanotechnology holds significant promise for creating novel products and enhancing processes due to the distinctive characteristics of nano based materials, namely their small size and extensive surface area. This is advantageous for applications in the food business and concerns regarding enhanced water absorption, release, and bioavailability of flavors. Polymeric nanoparticles have been extensively studied and applied in the pharmaceutical sector (Mora-Huertas et al., 2010). However, this technology has also made significant advancements in the fields of food and agricultural science. The polymeric nanoparticles (PNPs) have significantly influenced various fields in the past decade, owing to their distinct features and behaviors resulting from their distinctive size. They can be produced by the processes of polymerization and synthesis using preexisting polymers. Their size is a fundamental attribute, typically ranging from 5 to 10 nm, with a maximum size of around 1000 nm. However, the commonly observed range is usually between 100 and 500 nm (Crucho & Barros, 2017). Multiple studies indicate that nanostructured materials have significant promise in many different fields, particularly in delivering bioactive chemicals in the field of food science. PNPs have several benefits as carriers of biological chemicals, including as precise regulation of release, safeguarding of encapsulated agent molecules, and maintaining their unique orientation (Crucho & Barros, 2017). Polymeric nanoparticles are extensively utilized as biomaterials due to their attributes of facile manufacturing and design, excellent biocompatibility, a diverse array of designs, and notable bio-imitative properties. Moreover, they offer significant benefits when employed for transporting bioactive chemicals of interest, whether in food packaging or plant protection (Fig. 15.1). This is because they function as active carriers, thanks to their ability to control and/or modify the release of these molecules (Peppas & Narasimhan, 2014). Submicron-sized systems exhibit distinct surface properties compared to micrometric-sized systems and demonstrate a rapid diffusion rate coupled with a low viscosity level. These characteristics make them highly versatile for various applications in food processing and preservation (González-Reza et al., 2018). In addition, they have the capacity to enhance the stability and solubility of lipophilic substances in water-based solutions, surpassing the capabilities of micro and nanoemulsions. Various natural and synthetic polymers have been employed as encapsulating agents to provide stability and safeguard bioactive compounds from degradation factors such as light, pH, oxygen, and so on. Nevertheless, the choice of the encapsulating material is determined by the desired functionality of the system

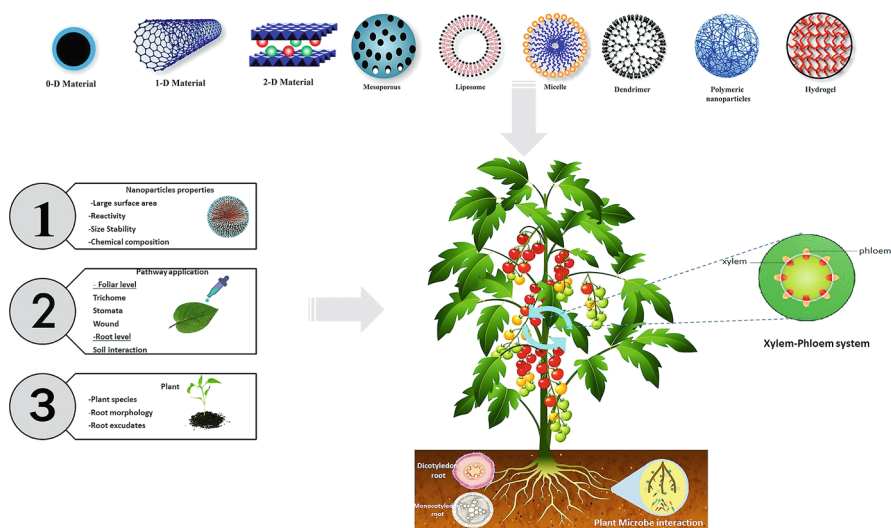


Fig. 15.1 Representation scheme of the main routes used by nanoparticles for translocation in plants

and its compatibility with the substance that is being transported. In the field of food, there are many biologically active compounds that have different characteristics and functions within the nanometric system. One of the most extensively researched aspects in the food business is the examination of the antioxidant and antibacterial properties of polymeric nanoparticles (Đorđević et al., 2014).

15.2 Common Polymeric Materials for Agricultural Applications

Polymeric nanocomposites, typically reinforced with $\leq 5\%$ nanoparticles, offer improved physical and functional properties due to their high surface area (Cao et al., 2011; Kashyap et al., 2015). Biopolymers like cellulose and chitosan are widely used due to their biodegradability, biocompatibility, and suitability for sustained-release formulations in agriculture (Kah & Hofmann, 2014). For instance, polymeric matrices such as polyvinylpyrrolidone have been employed to gradually release fungicides like tebuconazole and chlorothalonil (Liu et al., 2001), and polymeric nanocapsules have effectively delivered insecticides including ivermectin and acetamiprid. Chitosan-based carriers have also enabled controlled nutrient release, such as NPK fertilizers (Corradini et al., 2010).

15.2.1 Metal-Complexed Chitosan Nanoparticles

Chitosan can form stable complexes with metal ions (Cu, Zn, Ag), enhancing its antifungal and growth-promoting effects. Cu–chitosan nanoparticles, for example, improved seed germination and disease resistance in tomato and maize plants by activating defense enzymes and enhancing enzyme expression (Malerba & Cerana, 2018). Similarly, Zn–chitosan nanoparticles enhanced antioxidant activity and pathogen resistance in maize (Choudhary et al., 2017). Several studies have shown that foliar application or seed priming with chitosan-metal nanocomposites enhances plant immunity and growth performance under biotic stress (Dananjaya et al., 2017). Metal–chitosan combinations with Zn, Cu, Ni, and TiO₂ have demonstrated broad-spectrum antifungal activity against pathogens such as *Fusarium oxysporum*, *Botrytis cinerea*, and *Phytophthora capsici* (Huang et al., 2013; Brunel et al., 2013).

15.3 Synthesis Methods and Characterization for Polymeric Nanocarriers

Presently, numerous techniques have been documented for the production of bio-polymeric nanoparticles (BPNs) with varying geometries and surface charges. The capabilities and use of BPNs are dependent upon their shape. Spherical nanoparticles, in particular, have been found to possess a significant ability to penetrate cells (Zhang et al. 2012). Hence, there are certain criteria concerning the morphology of nanomaterials derived from biodegradable polymers, particularly when employed as carriers within the human body. The significance of this criterion becomes especially crucial when selecting the preparation process, as elaborated in the section dedicated to the synthesis of biodegradable polymeric nanoparticles.

15.3.1 The Ionic Gelation Method

Ionic gelation is a widely used method for synthesizing bio-polymeric nanoparticles (BPNs), relying on electrostatic interactions between ionic polymers and crosslinking agents (van der Linden & Foegeding, 2009). This method offers high nanoparticle stability and is effective for encapsulating biomolecules (Sullivan et al., 2018). Materials like chitosan, alginate, and starch are commonly employed. Fan et al. (2012) optimized chitosan nanoparticle synthesis using a 3.3:1 chitosan to sodium tripolyphosphate (TPP) ratio at pH 4.7–4.8, producing particles around 138.1 nm. Calvo et al. (1997) reported achieving particles as small as 26 nm by adjusting pH to 4.6 and using low-molecular-weight chitosan at a 3:1 chitosan:TPP ratio. Anand et al. (2018) adjusted pH to 6.0, yielding spherical nanoparticles (8–80 nm).

Liu et al. (2020) created negatively charged starch nanoparticles (50–100 nm) using carboxymethylation, and later reported another method involving oxidized starch and calcium ions, yielding 30–50 nm particles with size controlled by calcium concentration. Subramanian et al. (2014) synthesized chitosan–starch nanocomposites (173–297 nm) incorporating anticancer agents.

15.3.2 Nano-precipitation Method

The nano-precipitation method is a rapid, simple technique distinct from emulsion-based methods, as it does not require precursor emulsions. Hydrophobic polymers or lipids are dissolved in a polar organic solvent (e.g., ethanol, acetone, THF), then mixed with a large amount of non-solvent (usually water), causing phase separation and nanoparticle formation. The solvent is later removed by evaporation. Protective agents can be applied to nanoparticle surfaces to enhance drug loading and stability (Wan-Hong et al., 2020). El-Naggar et al. (2015) synthesized starch nanoparticles loaded with diclofenac sodium by mixing starch with sodium hydroxide, Tween-80, and sodium tripolyphosphate, then precipitating with ethanol. This yielded spherical particles ~21 nm, serving as drug carriers. Chin et al. (2011) produced starch nanoparticles (300–400 nm) by dissolving starch in sodium hydroxide and urea solutions before precipitation in ethanol; surfactants like Tween-80 and cetyltrimethylammonium bromide reduced particle sizes to 150–300 nm. Gutiérrez et al., 2020 reported starch nanoparticles ~14 nm formed by injecting starch solutions with sodium hydroxide and urea into ethanol at controlled rates. Dimethyl sulfoxide (DMSO) can also serve as a solvent, disrupting starch hydrogen bonds. Pan et al. (2022) used DMSO and ultrasound to create starch nanoparticles averaging ~69 nm after dialysis and lyophilization.

15.3.3 Microemulsion Method

Micro-emulsions are stable colloidal dispersions that are isotropic and transparent or clear. They consist of at least three components: a non-polar phase, a polar phase, and a surfactant. Microemulsions typically exhibit a structural arrangement where oil is dispersed in water (M/W) or water is dispersed in oil (W/M) (Asgari et al., 2019). The microemulsion approach involves introducing an aqueous polymer solution into an organic solvent containing a surfactant while homogenizing the resulting mixture. This results in the formation of a finely dispersed water-in-oil (W/AM) microemulsion, in which nanoparticles are deposited. The microemulsion approach enables the production of biodegradable polymer nanoparticles (Kafshgari et al., 2012).

Trinh and Hung synthesized starch nanoparticles using the microemulsion technique. A solution of starch with an alkaline pH was introduced into a mixture of ethanol, Tween-80, and soybean oil while being stirred. The resultant mixture was stirred incessantly for 1 h. These nanoparticles were separated using centrifugation and then subjected to lyophilization. The study carried out by Duyen and Van Hung (2021) yielded nanoparticles that were spherical in shape, with an average size ranging from 70 to 200 nm. The microemulsion process enables the synthesis of nanocomposite materials, including crosslinked polymers and polymers encapsulating metal nanoparticles. Wang et al., 2020 synthesized magnetic chitosan nanoparticles using the microemulsion technique. The process involved dissolving chitosan in a hydrochloric acid solution, followed by the addition of cyclohexane, hexanol-1, and divalent iron salt to the resultant solution while stirring.

The nanoparticles that were created were utilized as an adsorbent for albumin protein, as described by Wang et al., 2008.

Wang et al., 2016 synthesized starch nanoparticles by microemulsion crosslinking, using a similar procedure to Zhou et al. (2014). The only exception was the use of 1-hexadecyl-3-methylimidazolium bromide as the ionic liquid, instead of 1-octyl-3-methylimidazolium acetate. The study by Wang et al. (2016) yielded nanoparticles of unspecified morphology, with an average size of 80.5 nm. By utilizing ionic liquids, it becomes feasible to acquire nanoparticles of biodegradable polymers with a size of up to 100 nm. The microemulsion method is intricate in its application due to the multi-step process involved. This technique is appropriate for acquiring nanodrugs that are derived from biodegradable polymers. The utilization of ionic liquids in this technique presents possibilities for streamlining the technical aspects and reducing costs.

15.3.4 Coacervation Method

Coacervation refers to the natural occurrence of a highly concentrated liquid phase that forms spontaneously from a uniform solution of large molecules that have a low affinity for the solvent. Coacervation is a process where a uniform solution of charged macromolecules separates into two liquid phases, with one phase being rich in polymers and the other being the supernatant. The two liquid phases exhibit immiscibility, yet exhibit strong interactions, facilitating the creation of nanoparticles composed of various biopolymers (Kaloti & Bohidar, 2010).

Starch nanoparticles were synthesized by coacervation. This involved mixing solutions of pre-modified starch, which had either a positively charged amino group or a negatively charged carboxyl group, at various molar ratios. The mixing was done under agitation and at room temperature. Nanoparticles were synthesized in a time frame of 15 min. The nanoparticles were subjected to centrifugation and then freeze-dried. Using this technique, researchers were able to produce spherical nanoparticles. They determined that the best ratio for creating nanoparticles with the minimum size of 138.9 ± 0.3 nm was 1:3 (Barthold et al., 2016). Research has

demonstrated that by using a comparable approach, it is possible to create composite nanoparticles consisting of biodegradable polymers made from chitosan and carboxymethyl starch (Saboktakin et al., 2011).

15.3.5 *Electrospray Method*

The electrospray technique relies on many forces, including hydrodynamic and electromechanical forces. The fundamental components of this technique consist of a syringe pump, a nozzle with a cooling jacket, a high-voltage power source, and a metal manifold. Crucial variables in this procedure include the distance that exists between the point of the needle and the manifold, which determines the velocity at which the fluid flows through the nozzle, and the voltage that is delivered. This approach involves the flow of a solution containing the substance used to make the nanomaterial through a nozzle that is subjected to voltage. The solution is then sprayed onto the collector at different speeds. The collector serves as a grounding agent. Alternatively, specialized drums or solutions may be employed in place of the collector. This technique is commonly employed for the production of drug nanocrystals (Pawar et al., 2018), while there have also been studies exploring the generation of nanoparticles from biodegradable polymers using this approach.

The application of an electric charge to the polymer solution is crucial in the process of electro-spraying. By utilizing a high electric voltage, the droplet interface is distorted, leading to the formation of droplets that are only nanometer-sized (Bock et al., 2011). The suggested process posits that the application of an electric field to a liquid droplet results in the generation of an electrostatic force within the droplet, known as the Coulomb force. This force then competes with the adhesion force present in the droplet. When the Coulomb force exerted is greater than the adhesion force of the droplet, the surface tension is relieved, resulting in the creation of nanodroplets (Kurakula & Raghavendra Naveen, 2021).

Chitosan nanoparticles containing tea polyphenols were produced by Wang et al., 2020. A chitosan solution was produced in acetic acid, and tea polyphenols were subsequently added at different mass ratios. The pH of the combination was carefully regulated within the range of 4.6–4.7. A sodium tripolyphosphate solution was prepared. The mixture of chitosan and tea polyphenols was then introduced into the solution through a nozzle with a diameter of 0.5 mm. The nozzle was positioned at a distance of 5–15 cm. The mixture was fed at a rate of 0.25–1 mL/h, and a voltage of 10–20 kV was applied to the nozzle. The nanoparticles were separated using centrifugation and then subjected to lyophilization. The smallest size of chitosan nanoparticles with encapsulated tea polyphenols was determined to be 128 ± 13 nm, utilizing the specified parameters. The nozzle-to-solution distance is set at 5 cm, the spray rate is 1 mL/h, and the voltage is 15 kV, according to Wang et al. (2020).

Chitosan nanoparticles were produced using electrospraying utilizing a specialized voltage generation device. The electrospraying process involved a syringe with an internal needle diameter of 0.65 mm and a working distance of 10 cm. The

chitosan was dissolved in acetic acid and then administered at a flow rate ranging from 0.2 mL/h to 1.1 mL/h. Subsequently, it underwent a drying process under a vacuum environment. Chitosan nanoparticles can be produced using solutions of varying concentrations and molecular weights (Thien et al., 2012). It is important to mention this fact.

15.4 Applications of Nanopolymers in Plant Protection

Nanotechnology is advancing plant protection by enabling efficient delivery of active compounds with reduced ingredient use and stronger disease control. Polymeric nanomaterials—natural or synthetic—serve as carriers protecting and releasing bioactives, with green synthesis promoting sustainable agriculture. Nanoparticles from natural polymers like chitosan, alginate, starch, and pectin are biodegradable, low in toxicity, and compatible with organic and conventional farming. They enable controlled release of agrochemicals, improving efficacy and environmental safety (Rostamabadi et al., 2024). Biopolymeric nano-pesticides reduce toxicity while enhancing delivery to specific plant tissues. Nanopolymers like daphnetin-carboxymethyl chitosan nanoparticles boost plant immunity by activating defense enzymes (CAT, PPO) and upregulating pathogenesis-related proteins, improving resistance against pathogens such as *Ralstonia solanacearum* (Wang et al., 2023). They also facilitate plant microbiome engineering, targeted delivery of beneficial microbes, and genetic modulation for disease resistance (Dong et al., 2023). Chitosan exhibits strong antimicrobial properties, used to encapsulate fungicides for enhanced effectiveness and reduced environmental impact (Rani & Kaur, 2022). Starch and cellulose biopolymers control fungicide release, protecting plants and soil health (Kumar and Kumar 2022). Carboxymethyl chitosan nanoparticles activate systemic resistance in tobacco and other crops (Wang et al., 2023; Zamria et al., 2024). Natural polysaccharides like arabinogalactan and glycyrrhizin improve pesticide solubility and seed penetration, enhancing protection. Nano-priming and nanocomposites (e.g., thiol-gated silica, chitosan-based) enhance hormone delivery, growth, and pest resistance (Zhao et al., 2023). Polymers such as polylactic acid and polyethylene glycol contribute to plant defense induction. Nanoparticles manage pathogens by inducing systemic resistance, inhibiting pathogen replication, and reducing infection severity (Liang et al., 2018). Nanomaterials like nano-capsules and carbon-based particles aid hormone delivery and resistance induction (Jabran et al., 2024). Chitin nanofibers effectively induce resistance in cabbage and strawberry (Parada et al., 2018). Chitosan-gallic acid formulations exhibit antibacterial effects and promote systemic acquired resistance (Francesconi et al., 2024). Encapsulating systemic acquired resistance (SAR) proteins in chitosan nanoparticles enhances plant defense, as shown in papaya against *Erwinia mallotivora* (Zamria et al., 2024). Lanthanum oxide nanoparticles reduce disease severity and improve yield in cucumbers (Luo et al., 2023). PEI-coated gold nanoparticles (PEI-AuNPs) deliver genes and siRNA to silence defense genes,

balance ROS, enhance antioxidants, increase chlorophyll, and reduce bacterial infection, improving plant health and resistance (Qi et al., 2024). Nanopolymers also stimulate phytohormone production and synergize with beneficial microbes to boost nutrient uptake and crop yield, supported by precision farming for targeted application (Wang et al., 2023). However, challenges remain in standardization, safety evaluation, and regulatory approval to ensure safe, effective agricultural use (Yadollahi et al., 2009).

- *Nanoencapsulation of Growth Hormones by Chitosan Nanoparticle*

Agriculture and horticulture widely utilize plant growth regulators, such as auxins and gibberellins. An obstacle in utilizing these plant growth regulators (PGRs) is their susceptibility to degradation in the presence of temperature as well as light. Therefore, it is possible to enclose these chemicals within nanoparticles in order to enhance their physicochemical characteristics. Application of alginate/chitosan encapsulated gibberellic acid to *Phaseolus vulgaris* resulted in enhanced plant growth. The application of chitosan nanoparticles containing gibberellic acid resulted in a considerable enhancement in both size of leaves and the quantity of chlorophyll in the host plant, as reported by (Pereira et al., 2016, 2017). Additionally, The application of chitosan nanoparticles containing indole butyric acid resulted in a considerable enhancement in disease mangment as reported by (Imara et al., 2024).

15.4.1 Applications of Nanopolymers in Food Packaging

The achievement of postharvest treatment can be mediated using a new formulation to reduce the effective dose of pesticides. The combination of biopolymer-based nanomaterials offers the possibility of overcoming solubilization and dispersion problems associated with nanoparticles. Nanomaterials such as nanoclays or cellulose nanofibers are commonly incorporated into the biopolymer to allow a controlled release of fungicides (Luo et al., 2020). Furthermore, the support of the biopolymer can also decrease the biocide employed and offer a broader antimicrobial effect. Polymers are used for food packaging and plant protection purposes, and they have advantages such as reduced microbial infection, controlled release, and sustainability. The biopolymer is used as a carrier for fungicides and as part of recyclable or bio-based composite materials. By using nanotechnology and incorporating nanomaterials, the amount of pesticide used is reduced (Korbecka-Glinka et al., 2022). Polymeric-based nanomaterials are composite materials in which a continuous polymeric matrix is reinforced with nanoscale additives, such as nanoclays, nanosilver, silica, carbon nanotubes, and other nanoparticles. These materials exhibit exciting properties derived from integrating the remarkable physical properties of the inorganic nanoparticles combined with the mechanical, optical, and barrier properties of the polymeric matrix. Consequently, composite materials have fantastic potential for application in diverse areas, such as in the food supply chain, such as

carriers of active compounds, food safety applications, biosensors, food analysis, fresheners, and freshness indicators. (Mallakpour et al., 2021; Rosales et al., 2022). Biodegradable nano/micro-formulations made from biopolymers offer a sustainable alternative, capable of selective degradation by fungal enzymes to release encapsulated agrochemicals. Using xylan from corncobs, the first fungicide-loaded xylan-based nanocarriers were produced through interfacial polyaddition. These nanocarriers showed activity against pathogenic fungi responsible for plant diseases, while empty ones stimulated fungal growth, indicating xylan degradation triggers agrochemical release. This innovative approach expands the range of biodegradable nanocarriers for agrochemical delivery in agriculture and horticulture (Beckers et al., 2020; Salgado et al. 2021). Nanotechnology application in food packaging industry, primarily focusing on improve packaging, smart packaging, and active packaging to enhance food preservation, safety, and consumer communication.

- *Improve packaging*

Researchers and food manufacturers are focusing on biobased alternatives due to their benefits like biodegradability, non-toxicity, and structural flexibility. When used alone or in composites, they offer strong barrier qualities against grease, oxygen, microbes, air, and water. However, technological breakthroughs are needed for biobased polymers to break into the market successfully for sustainable packaging solutions (Mujtaba et al., 2022). Improve packaging utilizes various nanomaterial such as clay, silica, cellulose, chitosan, carbon nanotubes, and starch. These materials enhance packaging properties by providing flexibility, gaseous exchange, and temperature and humidity maintenance by main features such as, enhanced antimicrobial properties. And cost effective solution for food packaging. Clay is extensively researched in food packaging. Nanocomposites combining silicates and polymers lead to improved barrier properties, making them effective for food preservation (Cui et al., 2021).

- *Smart packaging*

Smart packaging is increasingly favored by consumers due to its ability to communicate the status of food products. This segment has seen growth due to consumer demand for safety and quality in food products. And development of packaging materials from renewable biopolymers (e.g. polysaccharides, proteins, lipids). Smart packaging is a rapidly evolving field that utilizes advanced technologies to improve packaging materials. It includes active packaging, which interacts with food to extend shelf life. Also, intelligent packaging provides information on food conditions in food packaging (Pereira de Abreu et al., 2012). Additionally, nanotechnology is used to enhance mechanical strength and safety. Recently, focusing on edible packaging made from natural materials reduces waste and provides nutrients, while biodegradable and compostable packaging breaks down naturally (Gupta et al., 2022). Sensors and indicators can monitor food conditions, and smart labels offer real-time product information. Smart packaging maintains food quality and safety and delivers essential information to consumers and supply chain stakeholders (Pal & Kant, 2020). For examples, thin films were made by combining chitosan and

cellulose nanocrystals using the casting process. Films with CNC/PVA/glycerol performed best, with good transmittance and thermal stability, making them suitable for food packaging (Varma & Vasudevan, 2024). Essential oils extracted from plants are important for their potential in food, pharmaceutical, and aromatherapy industries. They show antimicrobial and antioxidant properties, making them beneficial for food packaging. Research has highlighted their effectiveness against microorganisms and oxidants, extending food shelf life. However, further studies are needed to assess their safety and potential side effects before widespread use in food applications (Ribeiro-Santos et al., 2017). Furthermore, the concern over plastic packaging disposal has led to the development of biodegradable biopolymers. Researchers are focusing on natural pigments derived from plants and food waste (anthocyanins, curcumin, betalains, carotenoids, chlorophyll, brazilin, quercetin, etc.) to address consumer demand for quality monitoring in food packaging (Farrag et al., 2018). Utilizing these pigments with biopolymeric matrices, (starch, cellulose, chitin, gums, agar, etc.) “to create smart biodegradable films” have been developed to effectively monitor the quality of meat, seafood, milk, and other products. The results suggest that these innovative packaging materials have the potential to replace traditional plastic packaging, offering an economical, safe, non-toxic solution while promoting the valorization of food waste (Bhargava et al., 2020). Moreover, researchers are focusing on developing intelligent food packaging systems that provide real-time information to consumers about food quality and safety, preventing waste. Integrating 2D materials, such as graphene-based materials and MXene, has led to cost-effective and environmentally friendly packaging with enhanced performance. With high aspect ratios and hydrophobic nature, these materials improve barrier properties and mechanical strength. They also have high conductivity and catalytic activity, enabling their use in intelligent packaging, including sensors and smart labels. This technology enhances the monitoring and maintenance of food quality and safety in packaged products, significantly impacting the industry (Jafarzadeh et al., 2024).

15.4.2 Importance of Polymers in Composites for Plant Protection and Food Packaging

In recent years, nanomaterials have been widely used because of their optical, catalytic, magnetic, mechanical, and thermal properties. Providing methods not only for the production of food or beverages without contamination but also for storing products without loss lies in the development of polymer-based materials. However, the relative instability of these materials limits their effective use. For this reason, the safe conversion of biological waste resources into added-value natural biomaterials can be a solution to eliminate environmental challenges in food packaging (Mujtaba et al., 2022).

Polymers are one of the most important materials, widely used in many areas today from daily life, automotive, construction, and textile, to high technology. Growing environmental problems connected with waste disposal, especially of non-degradable polymers, is also a very important reason for increasing interest in natural polymers. The preparation of nanosystems with the help of nanotechnology has been regarded as an important factor in the use of these natural polymers, which have begun to play an increasingly important role, especially in plant protection and controlled release studies (Samir et al., 2022). There are also many studies in which nano biocomposites are prepared using polymer structures, and these composites are offered as alternatives with lower cost (bulk scale), higher thermal resistance (or gas barrier property), mechanical properties of the film and fiber, and better surface quality properties, which are not existent in polymer matrices (Fu et al., 2019; Shahbaz et al., 2024).

- *Plant Packaging Enhanced by Nano-polymer*

Plant foods need special packaging to ensure proper preservation from damage and post-harvest losses. The enhancement of polymer films used to package fruit and vegetables is currently a major area of research, especially when such enhancements can extend the shelf-life of produce (Kocira et al., 2021). Enhancements are being sought that not only improve the water barrier properties, but can control the gas exchange, maintain the water vapor transmission through the packaging, reduce water evaporation from produce, and lessen shrinkage, wilting, and browning. However, to date, the currently used synthetic materials have come under scrutiny for their non-biodegradable nature. This has resulted in recent interest being shown in the use of biodegradable polymers sourced from plants and other sustainable materials for such applications as packaging films and coatings. Among the several technologies introduced to develop active packaging materials with various functionalities, nanotechnology is one of the most promising, and it specifically includes the addition of nanostructures presented along a suitable matrix material (Abdullah et al., 2022).

- *Benefits and Efficiency of Nano-polymers in Plant Packaging*

As the demand for bio-polymer-based packaging materials increases, research and studies aiming to prevent microbial spoilage of food products are growing. A significant body of research has shown that bio-nano-based nanomaterials support the use of materials for food packaging because nanomaterials have become attractive substitutes for conventional materials in terms of their mechanical, barrier, optical, antimicrobial, and safety properties. These functional bio-nano-based materials have become commercially significant in two major areas, namely antimicrobial packaging and active packaging (Asgher et al., 2020). Food packaging is considered to be one of the most important types of packaging when it comes to human health and environmental safety. Research regarding sustainable packaging for fresh food products is paramount, encompassing numerous innovative organic residue-based biomaterials and is based on green chemistry and innovative technologies, including nanotechnologies. Green nanomaterials have been considered indispensable in the

Table 15.1 Showing the efficiency of some based nanopolymers in plant packaging

Fruit/ Vegetable	Type of nanocomposite	Impact of nanocomposite	Reference
Papaya	Pectin with zinc oxide	Reduced weight loss, maintained firmness, and titratable acidity	dos Santos et al. (2024)
Fruit and vegetable tomatoes	Silver+ polyvinyl alcohol or proteins or chitosan or titanium oxide or magnesium oxide or grapheme oxide	Extended shelf life, reduce microbial growth Enhance antifouling and antibiofouling properties of thin-film	Ding et al. (2024)
Fresh cut melon/citrus fruits	Gelatin-chitosan composite	Decreased color changes, reduced respiration rate, extended shelf life	Katiyar et al. (2021)
Citrus fruits	Wax-based nanoemulsions	Improved water barrier properties. Extend shelf life.	de Oliveira Filho et al. (2021)
Apple	Nanocellulose with orange essential oil	Improve bactericidal properties Extended shelf life	Li et al. (2022)
Apple	Chitosan/guar gum active packaging containing walnut green husk extract	Preservation of cut apple Extended shelf life	Jiang et al. (2022)
Orange	Alginate-chitosan with ZnO nanoparticles	Increase quality parameters (decrease changes in pH, weight loss, firmness, ascorbic acid concentration, etc.) Extended shelf life	Dulta et al. (2022)
Strawberry	Chitosan-glycine-betaine	Increased tissue firmness. Reduced decay. Extended shelf life	Bahmani et al. (2024)
Strawberry	Quercetin@ZIF-L/GO@AgNPs film-nanocomposite	Preservation of strawberry in room temperature Improve the storage and freshness of strawberry.	Yin et al. (2024)

development of new items for biodegradable and compostable packaging. Thus, a big focus has been on the development and study of many types of bio-nanocomposite materials, including nano-polymers for green and active packaging (Table 15.1) (Olawore et al., 2024).

15.4.3 Types of Polymer Nanocomposites Used in Food Packaging Active Packaging

Progress in nanocomposites containing bioactive compounds is transforming the field of food packaging. Nanoparticles such as carbon nanotubes, nanosilica, nanoclays, nanocellulose, and chitosan improve the quality of polymeric films by adding advanced properties. Nanocomposite films containing essential oils, bacteriocins, and other ingredients are beneficial for ensuring food safety. These new materials in the food are secure and effective substitutes for regular plastics, providing better mechanical, thermal, optical and barrier features (Brandelli, 2024). Previous studies discussed incorporating bioactive compounds such as calcium phosphates and delivery agents like poly(lactic-co-glycolic acid) (PLGA). Furthermore, studies addressed the role of chitosan in nanocomposite materials for various applications, including food preservation (Chen et al., 2023). Bioactive compounds like silver nanoparticles (Shankar et al., 2021), zinc oxide nanoparticles, titanium dioxide nanoparticles, chitosan, antimicrobial peptides, curcumin, calcium phosphates, poly(lactic-co-glycolic acid) (PLGA), gelatin, albumin, and hyaluronic acid are often used in nanocomposites. These compounds improve functionality by increasing antimicrobial properties of these nanocomposites, helping tissues heal, or allowing controlled release of active compounds (Kocira et al., 2021). They are chosen based on the nanocomposite's intended use and properties. Nanocomposites are used to package food. They included polymers like starch and chitosan mixed with nanofillers like carbon dots, cellulose nanofibers, and silver nanoparticles (Salama et al., 2021). These nanocomposites enhance packaging functionality by providing antimicrobial, antioxidant, and improved mechanical properties. The active and intelligent food packaging materials aim to interact with packaged food to preserve quality, enhance safety, and extend shelf life. These materials can be fabricated into different forms, such as films, coatings, and nanofibers, to meet various packaging needs and improve food safety, quality, and sustainability (Rhim et al., 2013).

For example, A small amount of non-toxic mustard oil added to PLGA micro-particles in double emulsion resulted in porous surface and interior morphology. The pore formation mechanism was studied using optical micrographs, SEM images, organic phase viscosity, and interfacial tension values. Pores were attributed to water droplets stabilized by mustard oil and PLGA chains within the polymer skin. Surface porosity was absent without mustard oil. Benzoic acid release from porous PLGA particles was studied over 60 days, showing controlled release affected by surface porosity manipulated by mustard oil amounts. Porous particles exhibited strong antimicrobial activity against *E. coli* and *S. aureus* due to increased surface area enhancing PLGA degradation and benzoic acid release (Table 15.2). Watermelon juice shelf life was extended by inhibiting natural microbe growth (Biswal et al. 2020). Furthermore, Clay-polymer nanocomposites are increasingly used in food packaging as a way to create active and bioactive materials (Cheikh et al., 2022). By incorporating bioactive compounds like antimicrobial agents (essential oil and silver

Table 15.2 Nanomaterials used in food products and packaging

Nanomaterials used	Applications in use
Titanium nitride (TiN)	Enhancements to polyethylene terephthalate, UV light screens, refrigerators, antibacterial and deodorant agents, and thermal characteristics
Carbon (C)	Additives, rubbers, silicones, printing inks
Silicon dioxide (SiO ₂)	The colours in ink for printing, paper and board, anti-slip agents, rubbery substances, silicone compounds
Aluminum (Al)	Polypropylene filler, coatings that withstand scratches and abrasions, enhanced barrier characteristics and ultraviolet (UV) filters
Silver (ag)	Recycled food containers, antimicrobial substances, antibiotic agents
Nanoclay	Enhancement of barrier characteristics
Zinc oxide (ZnO)	UV light filters, antibacterial and fungistatic chemicals, deodorant products, polyethylene glasses, and plastic films.

nanoparticles) and antioxidants into these nanocomposites, the packaging can improve its functional properties. The structure of the nanocomposites enhances properties such as barrier, mechanical, and thermal features compared to traditional polymers (Shankar et al., 2021). Additionally, clay nanofillers can serve as carriers for the controlled release of bioactive compounds (Ianchis et al., 2020). Recent studies are focused on developing nanocomposites with tailored release kinetics and improved bioactivity for food packaging. These materials offer benefits like extended shelf life, improved food safety, and reduced need for synthetic preservatives. However, challenges exist in ensuring the safety of nanomaterials in food contact and controlling the migration of compounds into food. Overall, clay-polymer nanocomposites show promise for creating sustainable and effective food packaging solutions (Rhim et al., 2013).

15.5 Safety and Regulatory Considerations

The increasing advancements in nanotechnology are expected to have a growing impact on the food business. The success of these developments will rely entirely on the thorough examination of regulatory matters. Several diverse government entities have shown interest in nanotechnology. This text provides an overview of the most recent findings from the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA). In July 2007, the Food and Drug Administration (FDA) released its Nanotechnology Task Force Report. In light of the potential for swift commercialization in this field, the FDA report suggests that the agency should consider providing guidance to the industry regarding the specific information that needs to be submitted to the FDA regarding nanoproducts. Additionally, the report suggests that the regulatory status of products may need to be re-evaluated when nanoscale materials are used. The FDA is currently working on a guidance paper for nanotechnology to help manufacturers assure product safety.

This document is expected to be completed and available by the end of 2010. Additional details can be found at <http://www.nano.gov>. Further details can be accessed on the National Cancer Institute website at <http://nano.cancer.gov>. The European Food Safety Authority (EFSA) has taken the lead in regulating the assessment of risks associated with nanotechnology. In February 2009, EFSA completed its evaluation of the potential risks of nanotechnologies for food and feed. It provided scientific guidance on the potential risks that may arise from the application of nano-science and nanotechnologies to ensure the safety of food and feed (Silvestre et al., 2011). Due to the subject's multidisciplinary nature, the European Food Safety Authority (EFSA) Scientific Committee was given the responsibility. Nanotechnologies are said to provide numerous opportunities for use in the food and feed industry.

These include improving production and processing technology, enhancing food contact materials, monitoring food quality and freshness, ensuring better traceability and product security, modifying taste, texture, sensation, consistency, and fat content, as well as improving nutrient absorption. The current and short-term forecasted markets are predominantly dominated by food packaging. The EFSA completed its evaluation of the potential hazards associated with nanotechnologies, affirming the necessity of a prudent and individualized approach due to numerous uncertainties regarding their safe utilization. The lack of comprehensive information on various areas now creates ambiguities in risk assessment and potential applications in the food and feed sector. There are particular doubts regarding the challenge of characterizing, detecting, and measuring nanoparticles in food and feed. Additionally, there is minimal knowledge regarding the toxico-kinetics and toxicological aspects of nanoparticles. Our understanding of the present usage levels and potential exposure from applications and products in the food and feed sector is inadequate. The risk assessment framework, which includes hazard identification, hazard characterization, exposure assessment, and risk characterization, is deemed suitable for nanoparticles. Nevertheless, while evaluating the potential risks of nanoparticles in the food and feed sector, it is crucial to take into account the distinctive characteristics of the nanoparticles, in addition to the features shared with their non-nano counterparts. Different types of nanoparticles are anticipated to differ in terms of their toxicological effects. The existing evidence on the toxicity resulting from oral exposure to individual nanoparticles is very restricted. The majority of the information available on nanoparticle toxicity comes from research conducted in laboratory settings or studies that involved exposure through other routes.

The European Commission and Member States are currently involved in discussions over a working paper. This document has the potential to be transformed into a proposal for regulations concerning substances and materials that are complex and not addressed in other legislation. Until the passage and acceptance of the legislation, nano-materials will be regulated using a combination of overall European Union food regulations and more targeted restrictions on specific materials. The primary regulatory framework within the European Union pertaining to the utilization of materials that come into contact with food is still governed by Regulation (EC) 1935/2004. It is required that any material used for food contact must be

appropriately inert to prevent the transfer of elements that could potentially affect human health or cause undesirable changes in the composition or qualities of the food. This regulation applies to any substance that has the potential to transfer its components into food with adverse consequences, including the migration of “nano-components” from packaging materials. The Regulation also encompasses the utilization of “active packaging” and “intelligent packaging”. It acknowledges that these types of packaging are not inherently passive and, as a result, outlines the primary prerequisites for their implementation. Therefore, any substance at the nano-scale that is intended to be released must undergo evaluation as a direct food additive. The standard procedure involves including the material elements, additives, and other components in lists of approved ingredients. Regulations on these ingredients are imposed through restrictions on their migration into food products or limitations on the composition of the materials. These guidelines apply to nanomaterials as well.

However, the safe maximum migration limits established for macro-components cannot be directly applied to their nano-equivalents due to potential variations in their physical, chemical, or biological characteristics. The EU regulation also includes descriptions of test techniques. Prior determination is necessary to ascertain the validity of the current test techniques in relation to the potential transfer of nanoparticles from materials to meals. The European Commission and Member States are actively engaged in discussions over a working paper. This report has the potential to be transformed into a proposal for regulations concerning substances and materials that are complex and not addressed in other legislations. Until the enactment and acceptance of appropriate legislation, nano-materials will be regulated using a combination of overarching European Union food regulations and targeted restrictions on specific materials. Under the current EU legislation, manufacturers are explicitly responsible for ensuring the safety of their products. This entails doing a thorough risk assessment that takes into account facts related to migration, toxicity, and consumption. Currently, the U.S. Food and Drug Administration (FDA) does not explicitly mandate the safety testing of nanoparticles. However, manufacturers are obligated to give evidence demonstrating that the use of food products containing nanomaterials is not detrimental. The responsibility of proving the safety of the material under its intended conditions of usage lies with the manufacturing sector.

15.6 Future Perspectives and Conclusion

Nanocarriers, developed through polymeric nanoparticle surface technology, are now being used in food packaging for disease management and disease control. These nanoparticles are designed to transport medications or insecticides through various processes, enhancing therapeutic efficacy, reducing dosage, and mitigating systemic side effects. However, challenges in nanocarrier field development include biological obstacles, large-scale production, biocompatibility, intellectual property

issues, regulatory compliance, and cost efficiency. Researchers should develop customized disease management strategies for nanopesticides based on plant disease characteristics and simplify nanocarriers. Recent advances in nanotechnology have created unique opportunities to tackle issues in pesticide development, with different structures offering new platforms for producing highly efficient agents. Toxicity hazards arise from the build-up of nanotechnology-based products in undesired plant tissues, so it is crucial to assess the biologically active dispersion of nanoparticles after systemic administration. As nanoparticles show great promise in solid plant protection and food packaging, there is now a growing demand for more strategic combinations of pesticides and nanocarriers.

References

- Abdullah, Cai, J., Hafeez, M. A., Wang, Q., Farooq, S., Huang, Q., et al. (2022). Biopolymer-based functional films for packaging applications: A review. *Frontiers in Nutrition*, 9, 1000116.
- Anand, M., Sathyapriya, P., Maruthupandy, M., & Hameedha Beevi, A. (2018). Synthesis of chitosan nanoparticles by TPP and their potential mosquito Larvicidal application. *Frontiers in Laboratory Medicine*, 2, 72–78.
- Asgari, S., Saberi, A. H., McClements, D. J., & Lin, M. (2019). Microemulsions as nanoreactors for synthesis of biopolymer nanoparticles. *Trends in Food Science and Technology*, 86, 118–130.
- Asgher, M., Qamar, S. A., Bilal, M., & Iqbal, H. M. (2020). Bio-based active food packaging materials: Sustainable alternative to conventional petrochemical-based packaging materials. *Food Research International*, 137, 109625.
- Bahmani, R., Razavi, F., Mortazavi, S. N., Gohari, G., & Juárez-Maldonado, A. (2024). Enhancing postharvest quality and shelf life of strawberries through advanced coating technologies: A comprehensive investigation of chitosan and glycine betaine nanoparticle treatments. *Plants*, 13(8), 1136.
- Barthold, S., Kletting, S., Taffner, J., de Souza Carvalho-Wodarz, C., Lepeltier, E., Loretz, B., & Lehr, C.-M. (2016). Preparation of nanosized coacervates of positive and negative starch derivatives intended for pulmonary delivery of proteins. *Journal of Materials Chemistry B*, 4, 2377–2386.
- Beckers, S. J., Wetherbee, L., Fischer, J., & Wurm, F. R. (2020). Fungicide-loaded and biodegradable xylan-based nanocarriers. *Biopolymers*, 111(12), e23413.
- Bhargava, N., Sharanagat, V. S., Mor, R. S., & Kumar, K. (2020). Active and intelligent biodegradable packaging films using food and food waste-derived bioactive compounds: A review. *Trends in Food Science & Technology*, 105, 385–401.
- Biswal, A. K., Hariprasad, P., & Saha, S. (2020). Efficient and prolonged antibacterial activity from porous PLGA microparticles and their application in food preservation. *Materials Science and Engineering: C*, 108, 110496. <https://doi.org/10.1016/j.msec.2019.110496>
- Bock, N., Woodruff, M. A., Hutmacher, D. W., & Dargaville, T. R. (2011). Electrospraying, a reproducible method for production of polymeric microspheres for biomedical applications. *Polymers*, 3, 131–149.
- Brandelli, A. (2024). Nanocomposites and their application in antimicrobial packaging. *Frontiers in Chemistry*, 12, 1356304.
- Brunel, F., Gueddari, N. E. E., & Moerschbacher, B. M. (2013). Complexation of copper (II) with chitosan nanogels: Toward control of microbial growth. *Carbohydrate Polymers*, 92, 1348–1356.

- Calvo, P., Remuñan-López, C., Vila-Jato, J. L., & Alonso, M. J. (1997). Chitosan and chitosan/ethylene oxide-propylene oxide block copolymer nanoparticles as novel carriers for proteins and vaccines. *Pharmaceutical Research*, 14, 1431–1436.
- Cao, X., Habibi, Y., Magalhães, W. L. E., Rojas, O. J., & Lucia, L. A. (2011). Cellulose nanocrystals-based nanocomposites: Fruits of a novel biomass research and teaching platform. *Current Science*, 100, 1172–1176.
- Cheikh, D., Majdoub, H., & Darder, M. (2022). An overview of clay-polymer nanocomposites containing bioactive compounds for food packaging applications. *Applied Clay Science*, 216, 106335.
- Chen, M., Li, L., Xia, L., Kong, Y., Jiang, S., Chen, X., & Wang, H. (2023). Preparation of PLGA/ ϵ -polylysine nanofibers and their application for pork preservation. *Food Packaging and Shelf Life*, 35, 101031.
- Chin, S. F., Pang, S. C., & Tay, S. H. (2011). Size controlled synthesis of starch nanoparticles by a simple nanoprecipitation method. *Carbohydrate Polymers*, 86, 1817–1819.
- Choudhary, R. C., Kumaraswamy, R. V., Kumari, S., Sharma, S. S., Pal, A., Raliya, R., Biswas, P., & Saharan, V. (2017). Cu-chitosan nanoparticle boost defense responses and plant growth in maize (*Zea mays* L.). *Scientific Reports*, 7, 9754.
- Corradini, E., de Moura, M. R., & Mattos, L. H. C. (2010). A preliminary study of the incorporation of NPK fertilizer into chitosan nanoparticles. *Express Polymer Letters*, 4, 509–515.
- Crucho, C. I. C., & Barros, M. T. (2017). Polymeric nanoparticles: A study on the preparation variables and characterization methods. *Materials Science & Engineering C, Materials for Biological Applications*, 80, 771–784.
- Cui, Y., Cheng, M., Han, M., Zhang, R., & Wang, X. (2021). Characterization and release kinetics study of potato starch nanocomposite films containing mesoporous nano-silica incorporated with thyme essential oil. *International Journal of Biological Macromolecules*, 184, 566–573.
- Dananjaya, S., Erandani, W., Kim, C.-H., Nikapitiya, C., Lee, J., & De Zoysa, M. (2017). Comparative study on antifungal activities of chitosan nanoparticles and chitosan silver nanocomposites against *Fusarium oxysporum* species complex. *International Journal of Biological Macromolecules*, 105, 478–488.
- De Oliveira Filho, J. G., Miranda, M., Ferreira, M. D., & Plotto, A. (2021). Nanoemulsions as edible coatings: A potential strategy for fresh fruits and vegetables preservation. *Foods*, 10(10), 2438.
- Ding, X., Lin, H., Zhou, J., Lin, Z., Huang, Y., Chen, G., et al. (2024). Silver nanocomposites with enhanced shelf-life for fruit and vegetable preservation: Mechanisms, advances, and prospects. *Nanomaterials (Basel)*, 14(15), 1244.
- Dong, B. R., Jiang, R., Chen, J. F., Xiao, Y., Lv, Z. Y., & Chen, W. S. (2023). Strategic nanoparticle-mediated plant disease resistance. *Critical Reviews in Biotechnology*, 43(1), 22–37.
- Đordević, V., Balanč, B., Belščak-Cvitanović, A., Lević, S., Trifković, K., Kalušević, A., Kostić, I., Komes, D., Bugarski, B., & Nedović, V. (2014). Trends in encapsulation technologies for delivery of food bioactive compounds. *Food Engineering Reviews*, 7, 452–490.
- Dos Santos, J. S., Cagnin, C., de Freitas, B. S. M., da Silva, R. M., de Jesus, G. B. L., Belisário, C. M., et al. (2024). Nanocomposite coatings of pectin and oxide zinc nanoparticles to increase papaya shelf life. *Coatings*, 14(8), 990.
- Dulta, K., Koşarsoy Ağçeli, G., Thakur, A., Singh, S., Chauhan, P., & Chauhan, P. K. (2022). Development of alginate-chitosan based coating enriched with ZnO nanoparticles for increasing the shelf life of orange fruits (*Citrus sinensis* L.). *Journal of Polymers and the Environment*, 30(8), 3293–3306.
- Duyen, T. T. M., & Van Hung, P. (2021). Morphology, crystalline structure and digestibility of Debranched starch nanoparticles varying in average degree of polymerization and fabrication methods. *Carbohydrate Polymers*, 256, 117424.
- El-Naggar, M. E., El-Rafie, M. H., El-sheikh, M. A., El-Feky, G. S., & Hebeish, A. (2015). Synthesis, characterization, release kinetics and toxicity profile of drug-loaded starch nanoparticles. *International Journal of Biological Macromolecules*, 81, 718–729.

- Fan, W., Yan, W., Xu, Z., & Ni, H. (2012). Formation mechanism of monodisperse, low molecular weight chitosan nanoparticles by ionic gelation technique. *Colloids and Surfaces. B, Biointerfaces*, 90, 21–27.
- Farrag, Y., Ide, W., Montero, B., Rico, M., Rodríguez-Llamazares, S., Barral, L., & Bouza, R. (2018). Preparation of starch nanoparticles loaded with quercetin using nanoprecipitation technique. *International Journal of Biological Macromolecules*, 114, 426–433.
- Francesconi, S., Tagliavento, V., Ciarroni, S., Sestili, F., & Balestra, G. M. (2024). Chitosan-and gallic acid-based (NPF) displayed antibacterial activity against three pseudomonas spp. plant pathogens and boosted systemic acquired resistance in kiwifruit and olive plants. *Pest Management Science*, 80(3), 1300–1313.
- Fu, S., Sun, Z., Huang, P., Li, Y., & Hu, N. (2019). Some basic aspects of polymer nanocomposites: A critical review. *Nano Materials Science*, 1(1), 2–30.
- González-Reza, R. M., García-Betanzos, C. I., Sánchez-Valdes, L. I., Quintanar-Guerrero, D., Cornejo-Villegas, M. A., & Zambrano-Zaragoza, M. L. (2018). The functionalization of nanostructures and their potential applications in edible coatings. *Coatings*, 8(5), 160.
- Gupta, P., Toksha, B., & Rahaman, M. (2022). A review on biodegradable packaging films from vegetative and food waste. *The Chemical Record*, 22(7), e202100326.
- Gutiérrez, G., Morán, D., Marefati, A., Pürhagen, J., Rayner, M., & Matos, M. (2020). Synthesis of controlled size starch nanoparticles (SNPs). *Carbohydrate Polymers*, 250, 116938.
- Huang, Q., Jiao, Z., Li, M., Qiu, D., Liu, K., & Shi, H. (2013). Preparation, characterization antifungal activity and mechanism of chitosan/TiO₂ hybrid film against *Bipolaris maydis*. *Journal of Applied Polymer Science*, 128, 383.
- Ianchis, R., Ninciuleanu, C. M., Gifu, I. C., Alexandrescu, E., Nistor, C. L., Nitu, S., & Petcu, C. (2020). Hydrogel-clay nanocomposites as carriers for controlled release. *Current Medicinal Chemistry*, 27(6), 919–954.
- Imara, D. A., Ghebrial, E. W., EL-Abeid, S. E., Hussein, E. M., Elsayed, M. I., & Yousef, R. S. (2024). Reduction of oxidative damage caused by *Fusarium falciforme* and *Fusarium foetens* in schefflera plants using chitosan nanoparticles loaded with l-proline or indole butyric acid. *Chemical and Biological Technologies in Agriculture*, 11(1), 167.
- Jabran, M., Ali, M. A., Muzammil, S., Zahoor, A., Ali, F., Hussain, S., et al. (2024). Exploring the potential of nanomaterials (NMs) as diagnostic tools and disease resistance for crop pathogens. *Chemical and Biological Technologies in Agriculture*, 11(1), 75.
- Jafarzadeh, S., Nooshkam, M., Qazanfarzadeh, Z., Oladzadabbasabadi, N., Strachowski, P., Rabiee, N., et al. (2024). Unlocking the potential of 2D nanomaterials for sustainable intelligent packaging. *Chemical Engineering Journal*, 490, 151711.
- Jiang, L., Wang, F., Xie, X., Xie, C., Li, A., Xia, N., et al. (2022). Development and characterization of chitosan/guar gum active packaging containing walnut green husk extract and its application on fresh-cut apple preservation. *International Journal of Biological Macromolecules*, 209, 1307–1318.
- Kafshgari, M. H., Khorram, M., Mansouri, M., Samimi, A., & Osfouri, S. (2012). Preparation of alginate and chitosan nanoparticles using a new reverse micellar system. *Iranian Polymer Journal*, 21, 99–107.
- Kah, M., & Hofmann, T. (2014). Nanopesticide research: Current trends and future priorities. *Environment International*, 63, 224–235.
- Kaloti, M., & Bohidar, H. B. (2010). Kinetics of coacervation transition versus nanoparticle formation in chitosan–sodium tripolyphosphate solutions. *Colloids and Surfaces B: Biointerfaces*, 81, 165–173.
- Kashyap, P. L., Xiang, X., & Heiden, P. (2015). Chitosan nanoparticle-based delivery systems for sustainable agriculture. *International Journal of Biological Macromolecules*, 77, 36–51.
- Katiyar, V., Ghosh, T., Ghosh, T., Modu Aji, M., Das, M., & Katiyar, V. (2021). Biopolymer nanocomposites in edible food packaging: Opportunity and applications. In *Nanotechnology in edible food packaging: Food preservation practices for a sustainable future* (pp. 233–257).

- Kocira, A., Kozłowicz, K., Panasiewicz, K., Staniak, M., Szpunar-Krok, E., & Hortyńska, P. (2021). Polysaccharides as edible films and coatings: Characteristics and influence on fruit and vegetable quality—A review. *Agronomy*, 11(5), 813.
- Korbecka-Glinka, G., Piekarska, K., & Wiśniewska-Wrona, M. (2022). The use of carbohydrate biopolymers in plant protection against pathogenic fungi. *Polymers*, 14(14), 2854.
- Kumar, A., & Kumar, N. (2022). Advances in transparent polymer nanocomposites and their applications: A comprehensive review. *Polymer-Plastics Technology and Materials*, 61(9), 937–974. <https://doi.org/10.1080/25740881.2022.2029892>
- Kurakula, M., & Raghavendra Naveen, N. (2021). Electrospraying: A facile technology unfolding the chitosan based drug delivery and biomedical applications. *European Polymer Journal*, 147, 110326.
- Li, J., Zhang, F., Zhong, Y., Zhao, Y., Gao, P., Tian, F., et al. (2022). Emerging food packaging applications of cellulose nanocomposites: A review. *Polymers*, 14(19), 4025.
- Liang, W., Yu, A., Wang, G., Zheng, F., Jia, J., & Xu, H. (2018). Chitosan-based nanoparticles of avermectin to control pine wood nematodes. *International Journal of Biological Macromolecules*, 112, 258–263.
- Liu, Y., Heiden, P., Yan, L., & Laks, P. (2001). Use of nanoparicles for controlled release of biocides in solid wood. *Journal of Applied Polymer Science*, 79, 458–465.
- Liu, Q., Cai, W., Zhen, T., Ji, N., Dai, L., Xiong, L., & Sun, Q. (2020). Preparation of debranched starch nanoparticles by ionic gelation for encapsulation of epigallocatechin Gallate. *International Journal of Biological Macromolecules*, 161, 481–491.
- Luo, Y., Wang, Q., & Zhang, Y. (2020). Biopolymer-based nanotechnology approaches to deliver bioactive compounds for food applications: A perspective on the past, present, and future. *Journal of Agricultural and Food Chemistry*, 68(46), 12993–13000.
- Luo, X., Wang, Z., Wang, C., Yue, L., Tao, M., Elmer, W. H., et al. (2023). Nanomaterial size and surface modification mediate disease resistance activation in cucumber (*Cucumis sativus*). *ACS Nano*, 17(5), 4871–4885.
- Malerba, M., & Cerana, R. (2018). Recent advances of chitosan applications in plants. *Polymers*, 10, 118.
- Mallakpour, S., Hussain, C. M., Rosales, C., Iglesias-Montes, M. L., & Alvarez, V. (2021). Consumer nanoproducts based on polymer nanocomposites for food packaging. In *Handbook of Consumer Nanoproducts* (pp. 1–23).
- Mora-Hurtas, C. E., Fessi, H., & Elaissari, A. (2010). Polymer-based nanocapsules for drug delivery. *International Journal of Pharmaceutics*, 385, 113–142. <https://doi.org/10.1016/j.ijpharm.2009.10.018>
- Mujtaba, M., Lipponen, J., Ojanen, M., Puttonen, S., & Vaittinen, H. (2022). Trends and challenges in the development of bio-based barrier coating materials for paper/cardboard food packaging; a review. *Science of the Total Environment*, 851, 158328.
- O’Callaghan, K. A. M., & Kerry, J. P. (2016). Consumer attitudes towards the application of smart packaging technologies to cheese products. *Food Packaging and Shelf Life*, 9, 1–9.
- Olaware, O., Ogunmola, M., & Desai, S. (2024). Engineered nanomaterial coatings for food packaging: Design, manufacturing, regulatory, and sustainability implications. *Micromachines*, 15(2), 245.
- Pal, A., & Kant, K. (2020). Smart sensing, communication, and control in perishable food supply chain. *ACM Transactions on Sensor Networks*, 16(1), 1–41.
- Pan, X., Liu, P., Wang, Y., Yi, Y., Zhang, H., Qian, D.-W., Xiao, P., Shang, E., & Duan, J.-A. (2022). Synthesis of starch nanoparticles with controlled morphology and various adsorption rate for urea. *Food Chemistry*, 369, 130882.
- Parada, R. Y., Egusa, M., Aklog, Y. F., Miura, C., Ifuku, S., & Kaminaka, H. (2018). Optimization of nanofibrillation degree of chitin for induction of plant disease resistance: Elicitor activity and systemic resistance induced by chitin nanofiber in cabbage and strawberry. *International Journal of Biological Macromolecules*, 118, 2185–2192.

- Pawar, A., Thakkar, S., & Misra, M. (2018). A bird's eye view of nanoparticles prepared by Electrospraying: Advancements in drug delivery field. *Journal of Controlled Release*, 286, 179–200.
- Peppas, N. A., & Narasimhan, B. (2014). Mathematical models in drug delivery: How modeling has shaped the way we design new drug delivery systems. *Journal of Controlled Release*, 190, 75–81. <https://doi.org/10.1016/j.jconrel.2014.06.041>
- Pereira de Abreu, D. A., Cruz, J. M., & Paseiro Losada, P. (2012). Active and intelligent packaging for the food industry. *Food Reviews International*, 28(2), 146–187.
- Pereira, A. E. S., Sandoval-Herrera, L. E., Zavala-Betancourt, S. A., Oliveira, H. C., Ledezma-Perez, A. S., Romero, J., & Fraceto, L. F. (2016). C-polyglutamic acid/chitosan nanoparticles for the plant growth regulator gibberellic acid: Characterization and evaluation of biological activity. *Carbohydrate Polymers*, 157, 1862–1873.
- Pereira, A. E. S., Silva, P. M., Oliveira, J. L., Oliveira, H. C., & Fraceto, L. F. (2017). Chitosan nanoparticles as carrier systems for the plant growth hormone gibberellic acid. *Carbohydrate Polymers*, 150, 141–152.
- Qi, J., Li, Y., Yao, X., Li, G., Xu, W., Chen, L., et al. (2024). Rational design of ROS scavenging and fluorescent gold nanoparticles to deliver siRNA to improve plant resistance to pseudomonas syringae. *Journal of Nanobiotechnology*, 22(1), 446.
- Rani, R., & Kaur, P. (2022). Polymeric nano-fungicides for the management of fungal diseases in crops. In *Nanotechnology in agriculture and environmental science* (pp. 82–98). CRC Press.
- Rhim, J. W., Park, H. M., & Ha, C. S. (2013). Bio-nanocomposites for food packaging applications. *Progress in Polymer Science*, 38(10–11), 1629–1652.
- Ribeiro-Santos, R., Andrade, M., de Melo, N. R., & Sanches-Silva, A. (2017). Use of essential oils in active food packaging: Recent advances and future trends. *Trends in Food Science & Technology*, 61, 132–140.
- Rosales, C., Iglesias-Montes, M. L., & Alvarez, V. A. (2022). Consumer Nanoproducts based on polymer nanocomposites for food packaging. In *Handbook of consumer Nanoproducts* (pp. 1277–1299). Springer.
- Rostamabadi, H., Demirkesen, I., Colussi, R., Roy, S., Tabassum, N., de Oliveira Filho, J. G., et al. (2024). Recent trends in the application of films and coatings based on starch, cellulose, chitin, chitosan, xanthan, gellan, pullulan, Arabic gum, alginate, pectin, and carrageenan in food packaging. *Food Frontiers*, 5(2), 350–391.
- Saboktakin, M. R., Tabatabaie, R. M., Maharramov, A., & Ramazanov, M. A. (2011). Synthesis and in vitro evaluation of carboxymethyl starch–chitosan nanoparticles as drug delivery system to the colon. *International Journal of Biological Macromolecules*, 48, 381–385.
- Salama, A., Abouzeid, R. E., Owda, M. E., Cruz-Maya, I., & Guarino, V. (2021). Cellulose–silver composites materials: Preparation and applications. *Biomolecules*, 11(11), 1684.
- Samir, A., Ashour, F. H., Hakim, A. A., & Bassyouni, M. (2022). Recent advances in biodegradable polymers for sustainable applications. *Npj Materials Degradation*, 6(1), 68.
- Salgado, P. R., Di Giorgio, L., Musso, Y. S., & Mauri, A. N. (2021). Recent developments in smart food packaging focused on biobased and biodegradable polymers. *Frontiers in Sustainable Food Systems*, 5. <https://doi.org/10.3389/fsufs.2021.630393>
- Shahbaz, M., Naeem, H., Murtaza, S., Ul-Huda, N., Tayyab, M., Hamza, A., & Momal, U. (2024). Application of starch as an active ingredient for the fabrication of nanocomposite in food packaging. In *Starch based nanomaterials for food packaging* (pp. 161–208). Academic.
- Shankar, S., Khodaei, D., & Lacroix, M. (2021). Effect of chitosan/essential oils/silver nanoparticles composite films packaging and gamma irradiation on shelf life of strawberries. *Food Hydrocolloids*, 117, 106750.
- Silvestre, C., Duraccio, D., & Cimmino, S. (2011). Food packaging based on polymer nanomaterials. *Progress in Polymer Science*, 36(12), 1766–1782.
- Subramanian, S. B., Francis, A. P., & Devasena, T. (2014). Chitosan–starch nanocomposite particles as a drug carrier for the delivery of bis-desmethoxy curcumin analog. *Carbohydrate Polymers*, 114, 170–178.

- Sullivan, D. J., Cruz-Romero, M., Collins, T., Cummins, E., Kerry, J. P., & Morris, M. A. (2018). Synthesis of monodisperse chitosan nanoparticles. *Food Hydrocolloids*, 83, 355–364.
- Thien, D. V. H., Hsiao, S. W., & Ho, M. H. (2012). Synthesis of Electro sprayed chitosan nanoparticles for drug sustained release. *Nano Life*, 2, 1250003.
- US National Nanotechnology Initiative. (2018). *What is nanotechnology?* Nano.gov, www.nano.gov/nanotech-101/what/definition. Accessed 9 Feb 2018.
- van der Linden, E., & Foegeding, E. A. (2009). Gelation. In *Modern biopolymer science* (pp. 29–91). Elsevier. ISBN 978-0-12-374195-0.
- Varma, R., & Vasudevan, S. (2024). Synthesis of composite films using polymer blends of chitosan and cellulose nanocrystals from marine origin. *Journal of Materials Science: Materials in Engineering*, 19(1), 6.
- Wang, Y., Wang, X., Luo, G., & Dai, Y. (2008). Adsorption of Bovin serum albumin (BSA) onto the magnetic chitosan nanoparticles prepared by a microemulsion system. *Bioresource Technology*, 99, 3881–3884.
- Wang, X., Cheng, J., Ji, G., Peng, X., & Luo, Z. (2016). Starch nanoparticles prepared in a two ionic liquid based microemulsion system and their drug loading and release properties. *RSC Advances*, 6, 4751–4757.
- Wang, Y., Zhang, R., Qin, W., Dai, J., Zhang, Q., Lee, K., & Liu, Y. (2020). Physicochemical properties of gelatin films containing tea polyphenol-loaded chitosan nanoparticles generated by electrospray. *Materials and Design*, 185, 108277.
- Wang, Y., Yang, L., Zhou, X., Wang, Y., Liang, Y., Luo, B., et al. (2023). Molecular mechanism of plant elicitor daphnetin-carboxymethyl chitosan nanoparticles against *Ralstonia solanacearum* by activating plant system resistance. *International Journal of Biological Macromolecules*, 241, 124580.
- Wan-Hong, C., Suk-Fun, C., Pang, S.-C., & Kok, K.-Y. (2020). Synthesis and characterisation of Piperine-loaded starch nanoparticles. *Journal of Physical Science*, 31, 57–68.
- Yadollahi, A., Arzani, K., & Khoshghalb, H. (2009). The role of nanotechnology in horticultural crops postharvest management. *Acta Horticulturae*, 875, 49–56.
- Yin, C., Ding, X., Lin, Z., Cao, J., Shi, W., Wang, J., et al. (2024). Preparation and characterization of quercetin@ ZIF-L/GO@ AgNPs nanocomposite film for room-temperature strawberry preservation. *Food Chemistry*, 450, 139411.
- Zamria, N. B., Wahidb, N. S., Bakar, N. A., Sohaimeb, M. Z., Azlina, N., & Masdorb, N. S. M. N. (2024). Unlocking the potential of chitosan nanoparticle as a carrier for systemic acquired resistance (SAR)-inducing recombinant protein: A preliminary study. *Asia-Pacific Journal of Molecular Biology and Biotechnology*, 32(1), 44–56.
- Zhang, X. W., Jia, L. J., Zhang, Y., Jiang, G., Li, X., Zhang, D., & Tang, W. H. (2012). In planta stage-specific fungal gene profiling elucidates the molecular strategies of *Fusarium graminearum* growing inside wheat coleoptiles. *Plant Cell*, 24(12), 5159–5176. <https://doi.org/10.1105/tpc.112.105957>
- Zhao, L., Zhou, X., Kang, Z., Peralta-Videa, J. R., & Zhu, Y. G. (2023). Nano-enabled seed treatment: A new and sustainable approach to engineering climate-resilient crops. *Science of the Total Environment*, 910, 168640.
- Zhou, G., Luo, Z., & Fu, X. (2014). Preparation and characterization of starch nanoparticles in ionic liquid-in-oil microemulsions system. *Industrial Crops and Products*, 52, 105–110.

Chapter 16

Application and Risks of Nanopesticides in Agriculture



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Abstract The application of nanopesticides in agriculture presents a promising solution for enhancing pest management while reducing environmental impact. Nanobased pesticides including fungicides, herbicides, molluscicides, nematicides, miticides and nanoparticulate growth regulators, have demonstrated efficacy against a broad spectrum of pests, including fungi, bacteria, virus, insects, rodents, weeds and mites. These formulations offer several advantages, such as increased efficiency, reduced dosage requirements, lower environmental impact, and improved crop yield etc. However, the environmental and health risks associated with nanopesticides are significant. Nanoscale based formulations can pose environmental concerns, particularly regarding their persistence in soil and water and their impact on non-target organisms. The behaviour of these nanoparticles is influenced by chemical factors such as pH and ionic strength, raising concerns about direct toxicity, durability, bioavailability, degradation, and the fate of the carrier materials. Potential toxicity is a critical issue, as exposure to pesticides has been linked to a range of severe health conditions and harsh environmental issues. Additionally, bioaccumulation of persistent organic pollutants through the food chain and the development of resistance in target pests further complicate pest management strategies. Therefore, while nanopesticides offer potential benefits in agriculture, their application requires careful risk assessment and management to mitigate potential environmental and health impacts.

Keywords Nanopesticide · Nanopesticide application · Nanoparticle · Risk assessment · Toxicology · Nanobased pest management

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16.1 Introduction

Agroecosystems host plant and animal species adapted to conventionally managed agricultural areas or those characterized by labor-intensive, diversified, small-scale farming methods without chemical pesticides. Pesticide residues are not confined to the application sites alone but can disperse into surrounding landscapes, extending their impact to ecologically sensitive and protected areas (Brühl et al., 2024). In agriculture, nanotechnology has shown great promise in offering novel solutions to issues related to plant protection, such as disease and pest infestation (Fu et al., 2020). The potential of nanotechnology to alter materials at the microscopic level has the potential to completely transform plant protection tactics (Kim et al., 2018). Nanoparticles, typically measuring between 10 and 100 nanometers (nm), can be engineered to exhibit distinctive chemical, physical, and biological characteristics that set them apart from their bulk materials and molecular forms (Yang et al., 2008). Nanomaterials are particularly valued for their large surface area relative to their volume (Blecher et al., 2011), which enhances their interactions with biological systems and strengthens their functional performance to manage insect pests and plant diseases. Nanotechnology has revolutionized plant pathology by providing advanced tools to combat various plant diseases, including those caused by nematodes, bacteria, viruses, fungi, and phytoplasmas. Strong antimicrobial properties of nanoparticles like silver, copper, gold, zinc oxide and titanium dioxide lead to the rupture of cell membranes, hinder enzyme function, and obstruct microbial replication (Vijayreddy et al., 2023).

16.2 Types of Nano Pesticides

16.2.1 Nanoemulsion

Microemulsions (MEs) and nanoemulsions (NEs) are self-emulsifying colloidal systems characterized by an internal dispersed phase generally smaller than 100 nanometers in diameter (Anton & Vandamme, 2011). These systems are suspended within a liquid medium, and their unique size characteristics significantly improve various physicochemical properties such as bioavailability and stability. By decreasing the internal phase size, emulsions are able to minimize gravity-induced instabilities like sedimentation that typically affect larger particles. Moreover, their naturally low surface and interfacial tensions improve the distribution and penetration of active agents, leading to greater overall effectiveness (Tadros et al., 2004). A nanoemulsion designed for Hemiptera control incorporated 5% *M. subsericea* extract within an oil phase of 5% octyldodecyl myristate, stabilized with 5% surfactants (sorbitan monooleate/polysorbate 80). This system produced droplets averaging 155 nm in size with a PDI of 0.15 and showed effective insecticidal potential (Lucia et al., 2020). Several classes of natural substances are recognized for

their nematocidal effects. These include glucosinolates and their breakdown products, isothiocyanates, as well as aliphatic acids such as acetic, hexanoic, butyric, and decanoic acids. Alkaloids, piperamides, and flavonoids like quercetin-7-glucoside are also noteworthy. Limonoids (e.g., meliacins, azadirachtin), quassinoids (e.g., chaparrinone, glaucarubolone, klaineanone, samaderines B and E), together with saponins and triterpene acids (including 11-oxotriterpenic, pomolic, and ursolic acids), represent other major groups. Furthermore, compounds such as cyanogenic glycosides, polyacetylenes, phenolic acids (salicylic, gallic, caffeic), fatty acids (linoleic, oleic), and volatile molecules like ascaridole, 2-undecanone, and thymol significantly contribute to nematode suppression (Ntalli & Caboni, 2012a, b, 2017; Caboni & Ntalli, 2014). Atovaquone is being assessed for its potential to inhibit a wide range of protozoan parasites. The nanoemulsions with clove oil were shown to effectively suppress the growth of *Leishmania infantum* and *Leishmania amazonensis*. They were found to be less cytotoxic compared to the commonly used fungicidal amphotericin B, as confirmed through hemolytic assay results (da Silva Cardoso et al., 2018). Tobacco alkaloids, including nicotine, are recognized as a distinct group of botanical pesticides. These compounds affect insect nervous systems by acting as acetylcholine mimics (Steppuhn et al., 2004). In a recent investigation, nanoemulsions were formulated with thyme oil (TO), either as a single component or blended with licorice aqueous extract (LAE), i.e., TFO4-10LAE, which exhibited promising results by inhibiting ergosterol production, thus displaying synergistic and antifungal activity (Arora et al., 2024). Compared to chemical pesticides, the TFO4-10LAE nanoemulsion was found to exert minimal adverse effects on the environment.

16.2.2 Nanoparticle

The word “nanoparticle” describes materials that exist within the nanometer size range. They generally consist of a solid matrix or core, which is frequently composed of metallic elements, although this is not always the case. Due to their minuscule size, nanoparticles exhibit notable differences in physical properties compared to larger bulk materials. These differences can include quantum effects such as superparamagnetism, and Coulomb blockade, surface plasmon resonance, which may have potential applications. Additionally, the increased surface area-to-volume ratio of nanoparticles enhances surface-related effects due to the high number of surface atoms and high specific surface area. Nanoparticles can be synthesized from a wide range of substances, such as metal oxides, ceramics, silicates, and magnetic compounds (Holister et al., 2003). For instance, nanoparticles may be programmed to release bioactive molecules upon sensing fungal lytic enzymes or after internalization within bacterial cells. In parasitic plants such as *Orobanch* species, activation could occur through recognition of parasite-derived enzymes, including pectin methyl esterases. Such smart nanocarriers would essentially act as an artificial immune system in plants, enabling the controlled release of toxic compounds only

at the required site and stage of infection, particularly during the underground development of the parasite (Losner-Goshen et al., 1998). Nanoparticles have recently been added to RNA interference (RNAi)-based pest control, which has proven to be a more effective and focused strategy (Yan et al., 2021). One of the major rice pests, the white-backed planthopper (*Sogatella furcifera*), has been successfully controlled under field conditions using star polymer (SPC) nanoparticles, a dendritic cationic macromolecular system. When combined with dsRNAs, this method showed a drastic reduction in the pest population. The dsRNA targeted SfVHA-F, SfVHA-c2 and SfVHA-a2 genes, and the SPC nanoparticles increased efficiency by properly penetrating the insect cuticle (Ma et al., 2024).

16.2.3 Nanosuspension

Compounds with low aqueous solubility are often incorporated into organic formulations either through dissolution in organic solvents or by preparation of emulsions. Despite this, such approaches typically require large quantities of solvents and stabilizing additives, which may result in undesirable side effects. A more universal approach to formulating poorly soluble drugs would be preferable. The bioavailability of poorly soluble compounds is highly dependent on their particle size. In the case of amorphous compounds, nanosuspensions with particle dimensions below 100 nm provide a promising strategy. Such formulations are typically produced by dissolving the drug together with suitable additives in an organic solvent, followed by rapid mixing with water. Crystalline compounds that are poorly soluble in both aqueous and organic solvents are often treated by micronization. In this approach, coarse drug powder is milled with water and additives, resulting in a suspension concentrate (SC) composed of ultrafine particles, generally measuring around 13 μm . Many new pesticides are less soluble and micronization by itself is often insufficient to achieve satisfactory enhancement of bioavailability. The next step is to produce nanocrystals, typically ranging from 200 to 500 nm, to improve their effectiveness in forming nanosuspensions (Lindfors et al., 2006; 2007). Reducing particle size can enhance the bioavailability of compounds such as AZ68 (Sigfridsson et al., 2007), buparvaquone (Kayser, 2001; Müller & Jacobs, 2002), danazol (Liversidge & Cundy, 1995), glucocorticoids (Kassem et al., 2007), naproxen (Liversidge & Conzentino, 1995), and tarazepide (Jacobs et al., 2000). Ding et al., 2024 demonstrated that chlorantraniliprole nanosuspension showed a lower residual effect and higher coverage on leaves. In addition to its enhanced foliar wetting and retention capabilities, the nanosuspension demonstrated superior dispersibility, further increasing its bioavailability against *Cnaphalocrocis medinalis*.

16.2.4 Nanocapsule

The term “nanocapsule” typically applies to devices with a structure consisting of a thin outer shell (or coating) enclosing a great internal cavity. The most beneficial nanomaterials are core-shell nanocapsules, which contain a pesticide in the core. This encapsulation technology is revolutionizing drug delivery in medical field and the application of fertilizers and pesticides in agriculture. Nanocapsules, generally made from polymers, contain an active substance within their protective shell. The shell serves to shield the chemical from external damage, enhance its solubility, and facilitate its penetration through tissues. Furthermore, the release of the encapsulated substance can be precisely controlled, for instance by modifying external factors such as pH. Such a property endows nanocapsules with high efficiency in targeted delivery applications, allowing the active compound to be released only when specific conditions are met, such as alkaline environment in stomach of insects. In agricultural research, liposomes have primarily served as model systems for plant organelle membranes, aiding studies on aging, desiccation, freeze tolerance, and the effects of toxins and pesticides. Recently, polymers have become fundamental in the development of nanocapsules (Teixeira et al., 2005). Similarly, chitosan and its oligomers are widely recognized in agricultural applications due to their antimicrobial properties. These oligomers not only display antifungal and antibacterial activity but also act as elicitors of plant defense mechanisms. Additionally, chitosan derivatives have shown insecticidal properties (Bautista-Baños et al., 2006; Trostel-Aziz et al., 2006). Broomrape tubercles, which behaves as significant nutrient and water sinking parasites, help in absorbing systemic herbicides. While this *Orobanche* spp. can be effectively managed by using sulfonylurea herbicides with multiple applications. Herbicides such as glyphosate, imidazolinones, and sulfonylureas can be individually encapsulated within polymeric shells. By incorporating surfactants, these shells can be tailored to improve cuticular penetration and subsequently applied systemically to leaves (Jurado-Expósito et al., 1996; Jurado-Expósito & Castejón-Muñoz, 1997). Nanocapsules not only enhance chemical delivery but also aid in their slow release, thus helping protect the environment. A nanocapsule developed using validamycin and thifluzamide as active ingredients helps control sheath blight of rice. The commercial loss is drastically reduced as they exhibit good foliar spray due to their smaller size. The synergistic ratios were 0.917 for the commercial formulation and 2.088 for the bifunctional pesticide nanocapsules and a 50% median effect concentration of 0.0082 µg/mL against *Rhizoctonia solani*. The bioactivity of the bifunctional system was markedly higher than that of the commercial formulations, demonstrating a clear synergistic interaction between the two active ingredients (Cui et al., 2020) (Fig. 16.1).

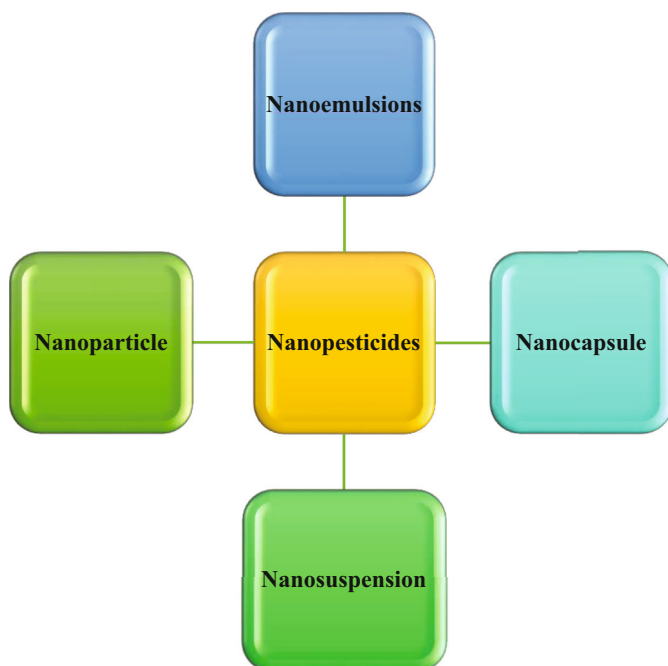


Fig. 16.1 Classification of nanopesticides

16.3 Carriers of Nanopesticides

Nanoparticles are increasingly utilized as carriers in agricultural formulations, enabling the encapsulation, adsorption, or binding of active molecules for more effective delivery. The versatility and effectiveness of these nanoparticles make them valuable tools in managing plant diseases, particularly in delivering pesticides and RNA interference (RNAi) inducing molecules. Commonly used nanoparticles in this context include chitosan nanoparticles, silica nanoparticles, layered double hydroxide (LDH), and solid lipid nanoparticles (SLNs) nanoparticles (Fig. 16.2). Each kind has unique benefits that promote the development of sustainable farming methods (Worrall et al., 2018).

16.3.1 Chitosan Nanoparticles as Carriers

Chitosan nanoparticles' beneficial structural and biological characteristics have made them more popular in the agricultural industry. As a cationic polysaccharide, chitosan dissolves readily in acidic aqueous media and is biodegradable, making it a favourable option for developing environmentally friendly formulations. However,

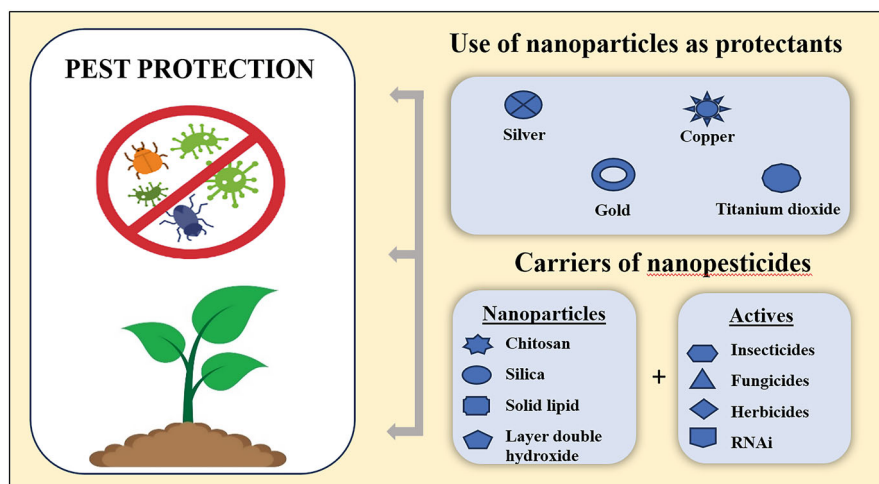


Fig. 16.2 Different compounds used as a nanoparticle with different actives for plant protection

its solubility is limited at physiological pH (around 7.4) because of its weak base nature (pKa 6.2 to 7). Chitosan is typically derived through amide hydrolysis using concentrated sodium hydroxide (NaOH) or enzymatic hydrolysis with chitin deacetylase. A major benefit of chitosan nanoparticles is their flexibility for formulation development. This is due to the availability of chitosan in varying molecular weights (500–1400 kDa) and different levels of acetylation, allowing for customized delivery systems tailored to specific agricultural needs. The amine groups present in chitosan's structure also enable further chemical modifications, enhancing its functionality as a carrier. Chitosan nanoparticles exhibit strong adhesion to different parts of plant, such as leaves surface and stems, thereby extending the retention time of agrochemicals at their target sites. This prolonged contact increases the effectiveness of the active compounds being delivered. Moreover, chitosan nanoparticles facilitate the penetration of active substances through plasma membranes, thus increasing their bioavailability and boosting their efficacy in managing plant diseases (Kashyap et al., 2015). A recent study demonstrated the fungicidal effect of chitosan-based nanoparticles against *Colletotrichum gloeosporioides*. (Wu et al., 2023).

16.3.2 Layered Double Hydroxides (LDHs)

LDHs are clay materials arranged in hexagonal layers, with active molecules accommodated within the interlayer spaces (Xu et al., 2006). These nanoparticles disintegrate in acidic environments when exposed to moisture and carbon dioxide, leading to the release of their contents. Delaminated LDH–lactate nanoparticles with positive charges are highly efficient in improving the translocation of bioactive

molecules through plant cell walls. Their unique charge and structural properties allow these nanoparticles to penetrate the cell wall barrier more efficiently, enabling precise delivery of the active compounds they transport. This improved transport mechanism not only increases the bioavailability of the materials but also amplifies their overall effectiveness in plant systems (Bao et al., 2016).

16.3.3 Solid Lipid Nanoparticles (SLNs) as Carriers

Solid lipid nanoparticles (SLNs) were first reported in 1991 as an improved alternative to conventional colloidal carriers such as liposomes, emulsions, and polymeric micro- or nanoparticles. They provide several advantages that make them highly suitable for agricultural practices. Active ingredients are better stabilized when encapsulated in these nanoparticles, preventing their degradation under environmental factors such as heat, light, and moisture (Wang et al., 2016). One notable advantage of SLNs is their capability to deliver active compounds in a controlled manner over an extended time. This prolonged release offers continuous protection against plant pathogens and lowers the requirement for repeated agrochemical use. The small size and lipid-based nature of SLNs also improve the bioavailability of encapsulated active ingredients, enabling more effective uptake by plant cells. SLNs can be engineered to target particular organs of plant or pathogens, thus reducing unintended effects and decreasing the amount of active ingredient needed. This targeted delivery system not only enhances the effectiveness of the active compounds but also promotes sustainable farming practices by minimizing environmental impact (Campos et al., 2014; Mishra et al., 2018).

16.3.4 Silica Nanoparticles

Such nanoparticles, with their controlled size and structure, are excellent delivery vehicles for pesticides. They encapsulate active ingredients, offering sustained release and protection from UV degradation. Leveraging silicon's role in boosting plant resilience, these nanoparticles are ideal for developing pest control products (Mody et al., 2014; Barik et al., 2008). Besides serving as a potential source of silica, silica nanoparticles are effective in controlling insect pests to manage range of pests while avoiding risks commonly associated with conventional pesticides, including residues, development of resistance, and environmental contamination. Silica materials offer several advantages over other materials owing to their superior mechanical stability compared to polymers and their capability to form nanostructures with high loading capacity for active substances. Amorphous silica is also considered biocompatible, as it has been classified as "Generally Recognized as Safe (GRAS)" by the U.S. Food and Drug Administration (Wang et al., 2024).

16.4 Methods of Application

16.4.1 *Foliar Sprays*

Foliar application of nanofertilizers enhances nutrient use efficiency (NUE) which promotes rapid plant development. These nanofertilizers react by penetrating the leaf cuticle, enabling controlled and targeted delivery of nutrients. Unlike when applied to soil, inorganic nutrients can become fixed in insoluble forms or be lost through leaching due to irrigation or rainfall (Alshaal & ElRamady, 2017), foliar application of nanofertilizers addresses these issues effectively. Additionally, this bypasses the limitations associated with restricted root growth, which can impede nutrient uptake. Foliar feeding is recognized as the quickest method to address nutrient deficiencies, enhancing both the yield and quality of crops (Romheld, 1999). This method further contributes to lowering environmental pollution while improving nutrient efficiency by decreasing the required fertilizer input. (Abou El-Nour et al., 2010). Although leaves facilitate gas exchange, the cuticle on their surface can limit the absorption of compounds (Schwab et al., 2016).

16.4.2 *Soil Treatments*

The increasing manufacture of nano-enabled products, along with the release of nanoparticles released from industries (e.g., wastewater from tannery) and household waste (e.g., sewage), presents notable risks to environmental sustainability. These nanoparticles contaminate both terrestrial and aquatic environments in large quantities (Ma et al., 2014; Eduok et al., 2015; Brown, 2017), affecting various ecosystems (Kulizhskiy et al., 2017). In agricultural fields, nanoparticles can be introduced into the soil through irrigation with untreated wastewater or by applying biosolids as fertilizers. (Rawat et al., 2018). Due to their biological persistence and resistance to degradation, nanoparticles can remain in the soil for prolonged periods. Their presence, whether alone or in combination with other substances, can impact soil fertility, alter soil microbiota, and modify the physiological and biochemical processes in essential plant species (Fayiga & Saha, 2017; Pittol et al., 2017; Yang et al., 2017).

16.4.3 *Seed Coatings*

Researchers worldwide have developed various “seed enhancement techniques” aimed at improving seed performance, coating with polymers, seed coloring, pelleting, nutrient fortification, and infusion. Among these, seed polymer coating stands out as particularly promising. In this technique, a controlled quantity of active

ingredients, along with a liquid polymer, is applied directly to the seed surface without altering its shape. This is a cost-effective way to enhance seed performance, allowing for the inclusion of essential components such as inoculants, nutrients, protectants, herbicides, hydrophilic substances, and suppliers of oxygen. Owing to their nanoscale size (10^{-9} meters) and large surface area, nanoparticles (NPs) display enhanced catalytic activity and reactivity, facilitating the efficient delivery of essential micronutrients such as zinc (Zn) and iron (Fe) via seed coating techniques. These micronutrients support normal physiological development in plants and serve as critical components of numerous enzymes involved in key metabolic processes in crops. Although these requisites are needed in only small quantities for seed treatment, their application in nanoparticle form is gaining attention for improving seed quality in certain crops (Krishna et al., 2017).

16.4.4 Post Harvest Treatments

Synthetic fungicides are widely employed across the globe to control postharvest diseases in horticultural produce. However, issues with these chemicals have led scientists to seek alternative methods. Over the past two decades, physical and biological methods, plant defense activators, and GRAS compounds have emerged as significant alternatives. Recently, treatments with nanomaterials have demonstrated potential and are being investigated as a means to decrease dependence on synthetic fungicides for controlling postharvest diseases. Various strategies are available for the preparation and synthesis of nanomaterials, broadly categorized into two main approaches: bottom-up and top-down approaches. Different types of nanomaterials including carbon-derived, metallic, ceramic, semiconductor, polymeric, and lipid-derived have been utilized, taking into account their synthesis, characterization (such as morphology, structure, particle diameter, specific surface area, along with their optical characteristics), and potential applications. In postharvest technology for fruits and vegetables, nanotechnology offers several benefits, including disease control, innovative packaging solutions, protection from gases and harmful rays, enhanced packaging appearance, and advanced labeling using nanobiosensors. Nanotechnology has promoted the synthesis of nanomaterials as antifungal agents for various commodities, demonstrating potential in managing diseases in citrus, grapes, bananas, apples, mangoes, peaches, and nectarines (Ruffo Roberto et al., 2019) (Fig. 16.3).

16.5 Application of Nanopesticides in Agriculture

Nanotechnology represents a groundbreaking frontier in modern agriculture, particularly in pesticide application. The growing global population has heightened the demand for increased agricultural productivity, with higher yields becoming a

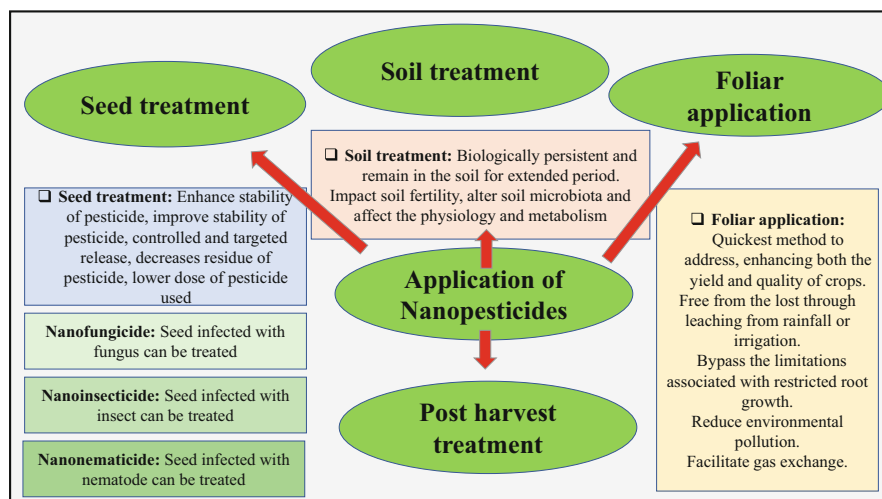


Fig. 16.3 Methods for application of nanopesticides

primary concern for many overpopulated nations. Traditionally, this demand has been met by extensive pesticide use, which has permeated farming systems worldwide (Verger & Boobis, 2013). Chemicals known as pesticides are used to eradicate or manage destructive organisms that seriously impair agricultural productivity. However, their widespread use has come at a cost, both economically and environmentally (Rakibuzzaman et al., 2018).

Plant diseases and insect pests result in significant periodic losses of crops, estimated at approximately 14% and 13%, respectively, resulting in a global economic loss of around \$2000 billion (Pimentel, 2009). Recent studies indicate that annual crop loss caused by pests alone is \$220 billion (Singh et al., 2023). Even though pesticides are widely used, less than 0.1% of them reach their intended locations. Through water runoff, spray drift, off-target deposition, photodegradation, and air dispersion during application, the majority of these chemicals are released into the environment. This inefficiency causes the surrounding ecosystems to get contaminated in addition to decreasing the efficacy of pest management (Pimentel, 1995; Carriger et al., 2006). To address these challenges, the agricultural sector has begun exploring the potential of nanotechnology to revolutionize pesticide application. By facilitating the creation of nanobased pesticides, nanotechnology presents an effective remedy for the drawbacks of traditional pesticides (Chhipa, 2017). Furthermore, nanopesticides improve the solubility of active chemicals that are poorly soluble, enabling a gradual and efficient release, thereby maximizing control of insects. Consequently, they can lower costs, increase crop yields, and reduce the frequency of applications, ultimately contributing to greater human and environmental safety (Gogos et al., 2012). This shift towards nanotechnology-based pesticides is poised to serve an important role in resilient farming systems,

delivering a more efficient and eco-friendlier alternative to traditional chemical pesticides.

Numerous pests, including insects, rodents, weeds, fungi, viruses, bacteria, and mites, have been effectively controlled using nanobased pesticides, which include, herbicides, nematicides, fungicides, miticides, molluscicides, and nanoparticulated growth regulators (Guang et al., 2013; Oliveira et al., 2015; Pereira et al., 2017; Antonoglou et al., 2018). Compared to traditional pesticides, these nanopesticides provide a number of benefits. Water diffusion, stability of chemicals, adhesion, permeability, and monitored release are among the formulation attributes that they improve (Zhao et al., 2017; Prasad et al., 2019). In addition, nanopesticides improve the solubility of active chemicals that are poorly soluble, enabling a gradual and efficient release, thereby maximizing pest management (Scrinis & Lyons, 2007; Kah et al., 2013). The strong reactivity of nanopesticides at the nanoscale, significantly surpasses the activity of bulk pesticides in pest control, is largely responsible for their effectiveness. Several chemical ingredients have proven effective in developing various nanopesticides, including silica, silver, carbon, and aluminum silicate (Asif et al., 2021). Strategic application of these nanoparticles can help manage particular pest problems. For instance, delayed release of water-soluble pesticides can be facilitated by porous silica, which targets pests over an extended period of time. Components of nanosilica can break down the lipid barrier in cutin layer of insect pests thus, increasing the efficacy of the pesticide (Liu et al., 2006; Ulrichs et al., 2005).

Research has demonstrated the potency of nanoscale alumina against insect pests such as *Sitophilus oryzae* (L.) and *Rhyzopertha dominica* (F.), with nanoaluminum particles showing high mortality ratio (Stadler et al., 2010). In a similar study, silver nanoparticles derived from the *Euphorbia prostrata* leaf extract exhibited complete lethality (100%) towards *Sitophilus oryzae* (L.) (Zahir et al., 2012). High mortality rates have been recorded as a result of the successful use of combined applications of zinc and silver nanoparticles, against destructive pests like *Aphis nerii* (Rouhani et al., 2012). Furthermore, ZnO NPs coated with *Bacillus thuringiensis* have proven to be successful nanopesticides, deferring the cowpea weevil's (*Callosobruchus maculatus*) larval and pupal development (Malaikozhundan et al., 2017).

The commercial adoption of nanoparticle-based pesticides has already begun, with several chemical companies marketing products such as Primo M.A.X.X., Subdue M.A.X.X., Banner M.A.X.X., Ospray's Chyella, and PennCap-M (Gouin, 2004). These advancements underscore the growing recognition of nanotechnology as a superior alternative to conventional pesticide use. The potential of nanotechnology in pesticide application is undeniable; Therefore, a thorough evaluation of the credibility and security of these novel materials is crucial due to their direct interaction with the environment (Das et al., 2018).

16.6 Advantages of Nano Pesticides

16.6.1 Increased Efficacy

Nanosized particles are increasingly used to enhance pesticide effectiveness through innovative formulations employing metals, polymers, copolymers, silica, carbon, lipids, and ceramics. These advanced techniques are pivotal in crop production, significantly improving the performance of enrichers and agrochemicals. Formulations of nanopesticides can improve their bioavailability, make them more soluble in water, and shield agrochemicals from environmental deterioration. This development is changing crop management of insects, weeds, and pathogens. Nanoformulations are particularly important for reducing the degradation of active ingredients, improving their solubility in water, and boosting their biological availability, thereby increasing the efficacy of pesticides (Chaud et al., [2021](#)).

16.6.2 Reduced Dosage Requirements

Precise modulation of nanoparticle size and exterior attributes allows for passive and active targeting of molecules upon parenteral delivery. These adjustments help regulate and prolong the release while in transit, ensuring deposition at the intended crop site and influencing distribution within plant tissues and clearance to enhance therapeutic efficacy while minimizing side effects and impeding non-target delivery of active ingredients. This approach allows for the use of smaller quantities of nanomaterials while achieving significantly higher effectiveness.

16.6.3 Lower Environmental Impact

Nanotechnology is a promising area in pest management that involves studying the interactions between nanomaterials and insects, formulating nanoemulsions for use as pesticides, and developing new nanopesticides. Nanoparticles synthesized from noble metals such as gold and silver are nontoxic towards human and exhibit high thermal stability. Traditional chemical methods for synthesizing nanopesticides, such as the microemulsion, polyol method, thermal, and electrochemical decomposition, often require toxic chemicals that can harm the environment. Hence, it is crucial to pursue more eco-conscious and sustainable approaches. Nanopesticides represent an emerging, environmentally friendly method of pest management (Dangi & Verma, [2021](#)).

16.6.4 Improved Crop Yields

Nanotechnology offers great potential in improving crop yields, safeguarding plants, diagnosing and monitoring plant diseases, increasing global food output, enhancing food quality, and minimizing resource wastage to support sustainable intensification. Its role is especially significant in agriculture and food sectors. In the agricultural sector, nanotechnology applications largely focus on precise agrochemical delivery, advanced sensing technologies for tracking crop conditions and environmental stresses, and enhancing plant characteristics to improve tolerance against stresses and pathogens. Traditional fertilizers lose 50–70% of nitrogen to soil leaching, and conventional fertilizers have not significantly improved nitrogen utilization efficiency (NUE) in plants. Additionally, only about 1% of applied pesticides effectively target pests or pathogens, whereas 99% interacts with unintended organisms and gets stored in plants. In contrast, emerging nano strategies suggest that nano nitrogen, with a high surface-to-volume ratio, it has the potential to be far more effective than standard polymer-coated slow-release nitrogen fertilizers. Similar improvements are noted in other nutrients like phosphorus, zinc, and titanium dioxide, as well as pesticides (Khan & Rizvi, 2017) (Table 16.1).

16.7 Risk Assessment and Limitations of Utilizing Nanobased Pesticides

Nanoscale-based formulations pose significant environmental concerns, particularly regarding their presence inside soil and water bodies and their impact on non-target organisms. The behaviour of these particles is affected by chemical conditions like pH and ionic concentration. Key issues include direct toxicity, durability, bioavailability, degradation, and the fate of the carrier (Malik et al., 2020). Some important points regarding their risk assessment are discussed below.

Table 16.1 Advantages and disadvantages of nanopesticides

Advantages	Disadvantages
1. Water solubility gets increased	Impact on non target pest
2. Protection from degradation	Release into the environment during production, storage and transport, leakage, consumer use and agricultural applications and disposal process.
3. Enhanced uptake by plants	Nanoparticles sprayed on plants, accumulate in human and animals through food and feed.
4. Dose reduction	Nanopesticides induces phytotoxicity
5. Reduced leaching and runoff	Inhibition of ectomycorrhiza and nitrification process in soil
6. Auto decomposition of pesticide	

16.7.1 Potential Toxicity

Pesticide use carries serious environmental and health consequences. Exposure to these toxic compounds has been associated with multiple health problems, such as neurological disorders, developmental abnormalities, respiratory illnesses, cancers, Parkinson's disease, infertility, hypoglycaemia or hyperglycemia, and genetic defects (Hu et al., 2015). Growing dependence on pesticides for pest and pathogen management underscores the urgency of reducing their excessive use and promoting viable alternative approaches. One of the most pressing concerns associated with conventional pesticide use is bioaccumulation, where persistent organic pollutants magnify via trophic transfer, leading to detrimental effects on ecosystem. Moreover, the development of resistance in target pests poses a significant challenge, further complicating pest management strategies (Chareonviriyaphap et al., 2013; Soko et al., 2015).

Nanoparticles (NPs) exhibit unique characteristics, including surface configuration and high reactivity, which are fundamental to processes such as dissolution, redox reactions, and ROS generation, thereby producing biological and toxicological outcomes absent in bulk materials of similar composition (Joner et al., 2007; Siegrist et al., 2008). The potential for a nanoparticle to cause toxicological effects through contact, ingestion, or inhalation is closely tied to its "nanoness." Engineered nanoparticles, particularly those measuring 30 nm or less in diameter, may pose risks to human and environmental health because of their distinctive properties. Numerous *in vitro* and *in vivo* investigations on NPs have produced inconsistent outcomes, even when using the same organism and nanoparticle type. Such discrepancies may stem from inadequate NP characterization prior to toxicity evaluation or the absence of standardized guidelines for NP risk assessment (Auffan et al., 2009). Researchers have tried to determine the most significant dose parameters that characterize NP toxicology in order to address these discrepancies in toxicity findings. Based on variables such as the particle's charge, number of particles, total surface area, concentration of mass, or particle size, several investigations have investigated whether a specific NP type causes toxicity. An understanding of these dose metrics, as underlined by various researchers, provides notable benefits. This involves aiding the incorporation of risk assessment findings into regulatory systems for the secure use of NPs, easing the comparison of study results, enabling authorities to establish health-related threshold values for each metric, and supporting risk evaluators in linking exposure and hazard data to assess the health impacts of different NP categories (Bouwmeester et al., 2009; Rossi et al., 2014).

Many kinds of nanoparticles (NPs), such as carbon-derived, organic, and inorganic nanoparticles, have undergone extensive research in nanotoxicology and risk assessment because of their numerous uses, particularly in agriculture (Rossi et al., 2014). The toxicological characteristics of these NPs have been extensively studied because of their potential for broad use. It has been discovered that certain NPs cause harmful consequences, whereas others show little to no toxicity. Much research has been done to evaluate the possible negative consequences of nanoparticles (NPs),

given their anticipated extensive usage in agriculture and the possibility of direct interactions that impact human biological system through ingestion. For example, solid lipid nanoparticles, polyethylene glycol (PEG), and poly (d,l-lactide-co-glycolide) (PLGA) NPs are polymeric NPs that have been associated with lung, immunotoxicity, and nephrotoxicity, respectively (Yang et al., 2017). In addition, both in vitro and in vivo investigations have addressed the possible toxicity of dendrimeric NPs, such as polyamidoamine and poly(propyleneimine), with findings suggesting concentration-dependent harmful effects. Therefore, to guarantee the safety of people and the environment, it is essential to carry out thorough and well-designed toxicity studies (Duncan & Izzo, 2005).

The toxicity of NPs, particularly inorganic ones, is well established, with numerous studies highlighting both Chronic and acute toxicity in plants, animals, and microorganisms. For instance, NPs like copper (Cu), copper oxide (CuO), selenium (Se), zinc (Zn), titanium dioxide (TiO₂), and zinc oxide (ZnO) have been linked to acute toxicity affecting organisms such as zebrafish and earthworms (Bouwmeester et al., 2009; Griffitt et al., 2008). Additionally, Nanoparticles of metal oxides, including CuO, ZnO, and TiO₂, been linked to a number of undesirable effects (Pérez et al., 2009; Matranga & Corsi, 2012; Mwaanga et al., 2017). Long-term or chronic effects are particularly concerning in agriculture with quantum dots and metal nanoparticles, such as cadmium telluride and cadmium selenide showing significant toxicity, including immunotoxicity, stress due to oxidation, and damage to DNA (Gagné et al., 2008; Kim et al., 2010). To stop aggregation and preserve their characteristics, inorganic nanoparticles are frequently coated or encapsulated, which can alter their behaviour and potentially reduce toxicity (Mwaanga et al., 2017).

The toxicological effects of carbon-containing nanoparticles (NPs) were thoroughly investigated because of the risk of direct human interaction. Research has shown mixed results, with some studies indicating low or no toxicity, while others report adverse effects, such as cytotoxicity in various human cells like hepatocytes (Hep G2 cells), alveolar epithelial (A549) cells, intestinal (P407) cells, and human embryonic kidney cells (HCT 116) and negative impacts on organisms exposed to fullerenes, carbon nanotubes, and nanofibers. Inclusive risk valuations are essential to guarantee the safe application of these NPs in agriculture, particularly considering the potential for delayed toxicity (Ostiguy et al., 2010; Tao et al., 2009; Pérez et al., 2009).

16.7.2 Regulatory Issues

Current insights into the environmental toxicity of nanopesticides are restricted, especially concerning their behavior and persistence in ecosystems. As a result, most countries mandate comprehensive regulatory review before these products can be commercially deployed. Premarket notice, evaluation of risks, and authorization are usually part of this process. Labeling and postmarket monitoring and

surveillance come next. Pesticides including nanosilver and other nanometals or metal oxides have been examined by the Scientific Advisory Panel of the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) in the United States. The Panel also out that existing techniques might not be enough for evaluating or forecasting the environmental effects of such nanomaterials, and that their health and environmental concerns could be different from those of traditional pesticides. The hazards that nanomaterials pose to the environment and human health are covered by current regulatory frameworks. The EU's Regulation (EC) No. 1107/2009 regulates plant protection products (PPPs), requiring prior clearance prior to market introduction. This process involves evaluation by the European Food Safety Authority (EFSA) for active ingredients and national authorities for product authorization. Regulation (EC) No 396/2005 addresses permissible residue limits in food and related official controls. Additionally, the EU's REACH legislation covers risks to workers and the environment, depending on the production, usage, or import volume of chemicals and nanomaterials. Risk assessments must consider both individual components and the nanopesticide as a whole. Laws governing agricultural nanoproducts differ from country to country in different parts of the world, like Asia, Africa, and Oceania. For example, although complete legislative and regulatory frameworks are still being developed, India recently published the "Guidelines for Evaluation of Nanoagri Input Products and Nanoagriproducts," which define nanofertilizers and nanopesticides (Grillo et al., 2021).

16.8 Future Directions in Research and Application

According to recent studies, by offering targeted pest control and assisting in the creation of smart nanosystems that tackle problems like ecological imbalance, food security issues, and lowered crop productivity, nanopesticides may reduce the negative effects of chemical pesticides. These nanopesticides offer long-term effectiveness and help solve environmental issues, such as pollution of nutrients in water bodies and the buildup of non-biodegradable material indifferent trophic level, through regulated release of active compounds. Improved solubility and stability of these nanoparticles also result in more effective pest management. However, further refinement of these techniques is necessary to fully benefit agriculture. Key aspects of nanopesticide development include the use of green chemistry, the improvement of traditional application methods, field-level evaluations, environmental impact assessments, and policy modifications for agricultural use. While agrochemical industries are working on smart nanopesticides with better solubility, stability, and targeted release, extensive research is still needed to understand their environmental impact (Malik et al., 2020).

16.9 Conclusion

Nanotechnology is not only a significant research strategy but also a transformative approach that simplifies the adoption of advanced technologies in agriculture. The remarkable effectiveness of nanotechnology-based pesticides, such as encapsulation of nanoparticle and nanoparticle-mediated DNA delivery to improve pest resistance, exemplifies the potential for smart and precision farming. By leveraging nanoscale strategies, nanotechnology can stimulate improvements in farming practices, reducing the hazardous use of chemicals and promoting sustainable agriculture. One of the main advantages of nanotechnology in agriculture is its capacity to improve current pesticide application strategies. Traditional farming practices often involve indiscriminate pesticide use without considering their actual efficiency or environmental persistence. This has led to issues such as pesticide resistance, environmental contamination, and health risks. Nanotechnology-based pesticides, with their controlled release mechanisms and enhanced reactivity, offer a more targeted and efficient approach. Moreover, the controlled release of nanopesticides can help maintain consistent pest control while minimizing environmental impact. This method minimizes the threat of non-target impacts in addition to lowering the total pesticide exposure in the environment, such as harmful impact on beneficial organisms or contamination of water sources. The precision offered by nanotechnology can improve the economic efficiency of pest control, as farmers can achieve the same level of protection with smaller quantities of pesticide. Therefore, nanotechnology holds significant promise for revolutionizing pesticide application and other aspects of agriculture by offering more efficient, targeted, and environmentally friendly solutions. These developments can aid in addressing a number of issues facing current agricultural practices, such as soil remediation, fertilizer management, and pest control. Research needs to continue on in order to fully grasp the potential benefits of nanotechnology in agriculture, its environmental and health impacts and to develop appropriate regulatory measures. As the agricultural sector evolves, nanotechnology will undoubtedly have a growingly significant part in promoting sustainable and precision farming practices.

References

- Abou El-Nour, K. M., Eftaiha, A. A., Al-Warthan, A., & Ammar, R. A. (2010). Synthesis and applications of silver nanoparticles. *Arabian Journal of Chemistry*, 3(3), 135–140. <https://doi.org/10.1016/j.arabjc.2010.04.008>
- Alshaal, T., & ElRamady, H. (2017). Foliar application: From plant nutrition to biofortification. *Environment, biodiversity and soil security*, 1, 71–83. <https://doi.org/10.21608/JENVBS.2017.1089.1006>
- Anton, N., & Vandamme, T. F. (2011). Nano-emulsions and micro-emulsions: Clarifications of the critical differences. *Pharmaceutical Research*, 28, 978–985. <https://doi.org/10.1007/s1109501003091>

- Antonoglou, O., Moustaka, J., Adamakis, I. D. S., Sperdouli, I., Pantazaki, A. A., Moustakas, M., & Dendrinou-Samara, C. (2018). Nanobrass CuZn nanoparticles as foliar spray nonphytotoxic fungicides. *ACS Applied Materials & Interfaces*, 10(5), 4450–4461. <https://doi.org/10.1021/acsami.7b17017>
- Arora, H., Naaz, F., Sharma, A., Dubey, S., Sharma, S., & Rajauria, G. (2024). Thyme-licorice nanoemulsion for anthracnose management in *Capsicum annuum* L. and life cycle assessment of its production. *Biocatalysis and Agricultural Biotechnology*, 56, 103029. <https://doi.org/10.1016/j.bcab.2024.103029>
- Asif, M., Islam, S., Malik, M. A., Dar, Z. M., Masood, A., Shafi, S., et al. (2021). Nano pesticides application in agriculture and their impact on environment. In *Agricultural development in Asia-potential use of nano-materials and nano-technology* (pp. 43–54). IntechOpen. <https://doi.org/10.5772/intechopen.78083>
- Auffan, M., Rose, J., Bottero, J. Y., Lowry, G. V., Jolivet, J. P., & Wiesner, M. R. (2009). Towards a definition of inorganic nanoparticles from an environmental, health and safety perspective. *Nature Nanotechnology*, 4(10), 634–641. <https://doi.org/10.1038/nnano.2009.242>
- Bao, W., Wang, J., Wang, Q., O'Hare, D., & Wan, Y. (2016). Layered double hydroxide nanotransporter for molecule delivery to intact plant cells. *Scientific Reports*, 6(1), 26738. <https://doi.org/10.1038/srep26738>
- Barik, T. K., Sahu, B., & Swain, V. (2008). Nanosilica—from medicine to pest control. *Parasitology Research*, 103, 253–258. <https://doi.org/10.1007/s00436-008-0975-7>
- Bautista-Baños, S., Hernandez-Lauzardo, A. N., Velazquez-Del Valle, M. G., Hernández-López, M., Barka, E. A., Bosquez-Molina, E., & Wilson, C. L. (2006). Chitosan as a potential natural compound to control pre and postharvest diseases of horticultural commodities. *Crop Protection*, 25(2), 108–118. <https://doi.org/10.1016/j.cropro.2005.03.010>
- Blecher, K., Nasir, A., & Friedman, A. (2011). The growing role of nanotechnology in combating infectious disease. *Virulence*, 2(5), 395–401. <https://doi.org/10.4161/viru.2.5.17035>
- Bouwmeester, H., Dekkers, S., Noordam, M. Y., Hagens, W. I., Bulder, A. S., De Heer, C., et al. (2009). Review of health safety aspects of nanotechnologies in food production. *Regulatory Toxicology and Pharmacology*, 53(1), 52–62. <https://doi.org/10.1016/j.yrtph.2008.10.008>
- Brown, J. (2017). Impact of silver nanoparticles on wastewater treatment. In *Nanotechnologies for environmental remediation: Applications and implications* (pp. 255–267). https://doi.org/10.1007/9783319560171_12
- Brühl, C. A., Engelhard, N., Bakanov, N., Wolfram, J., Hertoge, K., & Zaller, J. G. (2024). Widespread contamination of soils and vegetation with current use pesticide residues along altitudinal gradients in a European Alpine valley. *Communications Earth & Environment*, 5(1), 72. <https://doi.org/10.1038/s43247-024-01220-1>
- Caboni, P., & Ntalli, N. G. (2014). Botanical nematicides, recent findings. In *Biopesticides: State of the art and future opportunities* (pp. 145–157). American Chemical Society. <https://doi.org/10.1021/bk20141172.ch009>
- Campos, E. V. R., de Oliveira, J. L., & Fraceto, L. F. (2014). Applications of controlled release systems for fungicides, herbicides, acaricides, nutrients, and plant growth hormones: A review. *Advanced Science, Engineering and Medicine*, 6(4), 373–387. <https://doi.org/10.1166/asem.2014.1538>
- Carriger, J. F., Rand, G. M., Gardinali, P. R., Perry, W. B., Tompkins, M. S., & Fernandez, A. M. (2006). Pesticides of potential ecological concern in sediment from South Florida canals: An ecological risk prioritization for aquatic arthropods. *Soil & Sediment Contamination*, 15(1), 21–45. <https://doi.org/10.1080/15320380500363095>
- Chareonviriyaphap, T., Bangs, M. J., Suwonkerd, W., Kongmee, M., Corbel, V., & Ngoen-Klan, R. (2013). Review of insecticide resistance and behavioral avoidance of vectors of human diseases in Thailand. *Parasites & Vectors*, 6, 1–28. <https://doi.org/10.1186/175633056280>
- Chaud, M., Souto, E. B., Zielinska, A., Severino, P., Batain, F., Oliveira-Junior, J., & Alves, T. (2021). Nanopesticides in agriculture: Benefits and challenge in agricultural productivity,

- toxicological risks to human health and environment. *Toxics*, 9(6), 131. <https://doi.org/10.3390/toxics9060131>
- Chhipa, H. (2017). Nanofertilizers and nanopesticides for agriculture. *Environmental Chemistry Letters*, 15, 15–22. <https://doi.org/10.1007/s1031101606004>
- Cui, J., Sun, C., Wang, A., Wang, Y., Zhu, H., Shen, Y., et al. (2020). Dual-functionalized pesticide nanocapsule delivery system with improved spreading behavior and enhanced bioactivity. *Nanomaterials (Basel)*, 10(2), 220. <https://doi.org/10.3390/nano10020220>
- da Silva Cardoso, V., Vermelho, A. B., Ricci Junior, E., Almeida Rodrigues, I., Mazotto, A. M., & Supuran, C. T. (2018). Antileishmanial activity of sulphonamide nanoemulsions targeting the β -carbonic anhydrase from *Leishmania* species. *Journal of Enzyme Inhibition and Medicinal Chemistry*, 33(1), 850–857. <https://doi.org/10.1080/14756366.2018.1464364>
- Dangi, K., & Verma, A. K. (2021). Efficient & eco-friendly smart nano-pesticides: Emerging prospects for agriculture. *Materials Today: Proceedings*, 45, 3819–3824. <https://doi.org/10.1007/s1135602113060x>
- Das, S., Chakraborty, J., Chatterjee, S., & Kumar, H. (2018). Prospects of biosynthesized nanomaterials for the remediation of organic and inorganic environmental contaminants. *Environmental Science: Nano*, 5(12), 2784–2808. <https://doi.org/10.1039/C8EN00799C>
- Ding, X., Guo, L., Du, Q., Wang, T., Zeng, Z., Wang, Y., Cui, H., Gao, F., & Cui, B. (2024). Preparation and comprehensive evaluation of the efficacy and safety of chlorantraniliprole nanosuspension. *Toxics*, 12(1), 78. <https://doi.org/10.3390/toxics12010078>
- Duncan, R., & Izzo, L. (2005). Dendrimer biocompatibility and toxicity. *Advanced Drug Delivery Reviews*, 57(15), 2215–2237. <https://doi.org/10.1016/j.addr.2005.09.019>
- Eduok, S., Hendry, C., Ferguson, R., Martin, B., Villa, R., Jefferson, B., & Coulon, F. (2015). Insights into the effect of mixed engineered nanoparticles on activated sludge performance. *FEMS Microbiology Ecology*, 91(7), fiv082. <https://doi.org/10.1093/femsec/fiv006>
- Fayiga, A. O., & Saha, U. K. (2017). Nanoparticles in biosolids: Effect on soil health and crop growth. *Annals of Environmental Science and Toxicology*, 2(2), 059–067. <https://doi.org/10.17352/jenst.000012>
- Fu, L., Wang, Z., Dhankher, O. P., & Xing, B. (2020). Nanotechnology as a new sustainable approach for controlling crop diseases and increasing agricultural production. *Journal of Experimental Botany*, 71(2), 507–519. <https://doi.org/10.1093/jxb/erz314>
- Gagné, F., Auclair, J., Turcotte, P., Fournier, M., Gagnon, C., Sauvé, S., & Blaise, C. (2008). Ecotoxicity of CdTe quantum dots to freshwater mussels: Impacts on immune system, oxidative stress and genotoxicity. *Aquatic Toxicology*, 86(3), 333–340. <https://doi.org/10.1016/j.aquatox.2007.11.013>
- Gogos, A., Knauer, K., & Bucheli, T. D. (2012). Nanomaterials in plant protection and fertilization: Current state, foreseen applications, and research priorities. *Journal of Agricultural and Food Chemistry*, 60(39), 9781–9792. <https://doi.org/10.1021/jf302154y>
- Gouin, S. (2004). Microencapsulation: Industrial appraisal of existing technologies and trends. *Trends in Food Science & Technology*, 15(7–8), 330–347. <https://doi.org/10.1016/j.tifs.2003.10.005>
- Griffitt, R. J., Luo, J., Gao, J., Bonzongo, J. C., & Barber, D. S. (2008). Effects of particle composition and species on toxicity of metallic nanomaterials in aquatic organisms. *Environmental Toxicology and Chemistry*, 27(9), 1972–1978. <https://doi.org/10.1897/08-002.1>
- Grillo, R., Fraceto, L. F., Amorim, M. J., Scott-Fordsmand, J. J., Schoonjans, R., & Chaudhry, Q. (2021). Ecotoxicological and regulatory aspects of environmental sustainability of nanopesticides. *Journal of Hazardous Materials*, 404, 124148. <https://doi.org/10.1016/j.jhazmat.2020.124148>
- Guang, X.-Y., Wang, J.-J., He, Z.-G., Chen, G.-X., Lei, D., Dai, J.-J., & Yang, X.-H. (2013). Molluscicidal effects of nanosilver biological molluscicide and niclosamide. *Chinese Journal of Schistosomiasis Control*, 25(5), 503–505. <https://doi.org/10.5555/20143041447>
- Holister, P., Weener, J. W., Roman, C., & Harper, T. (2003). Nanoparticles. *Technology white papers*, 3, 1–11.

- Hu, R., Huang, X., Huang, J., Li, Y., Zhang, C., Yin, Y., et al. (2015). Long-and short-term health effects of pesticide exposure: A cohort study from China. *PLoS One*, 10(6), e0128766. <https://doi.org/10.1371/journal.pone.0128766>
- Jacobs, C., Kayser, O., & Müller, R. H. (2000). Nanosuspensions as a new approach for the formulation for the poorly soluble drug tarazepide. *International Journal of Pharmaceutics*, 196(2), 161–164. [https://doi.org/10.1016/S0378-5173\(99\)00412-3](https://doi.org/10.1016/S0378-5173(99)00412-3)
- Joner, E. J., Hartnik, T. & Amundsen, C. E. (2007). Environmental fate and ecotoxicity of engineered nanoparticles (Norwegian pollution control authority report no. TA-2304/2007). Norwegian Pollution Control Authority. doi:https://doi.org/10.1007/978-3-030-05144-0_5.
- Jurado-Expósito, M., García-Torres, L., & Castejón-Muñoz, M. (1997). Broad bean and lentil seed treatments with imidazolinones for the control of broomrape (*Orobanche crenata*). *The Journal of Agricultural Science*, 129(3), 307–314. <https://doi.org/10.1017/S0021859697004723>
- Jurado-Expósito, M., Castejón-Muñoz, M., & García-Torres, L. (1996). Broomrape (*Orobanche crenata*) control with imazethapyr applied to pea (*Pisum sativum*) seed. *Weed Technology*, 10(4), 774–780. <https://doi.org/10.1017/S0890037X0004080X>
- Kah, M., Beulke, S., Tiede, K., & Hofmann, T. (2013). Nanopesticides: State of knowledge, environmental fate, and exposure modeling. *Critical Reviews in Environmental Science and Technology*, 43(16), 1823–1867. <https://doi.org/10.1080/10643389.2012.671750>
- Kashyap, P. L., Xiang, X., & Heiden, P. (2015). Chitosan nanoparticle based delivery systems for sustainable agriculture. *International Journal of Biological Macromolecules*, 77, 36–51. <https://doi.org/10.1016/j.ijbiomac.2015.02.039>
- Kassem, M. A., Rahman, A. A., Ghorab, M. M., Ahmed, M. B., & Khalil, R. M. (2007). Nanosuspension as an ophthalmic delivery system for certain glucocorticoid drugs. *International Journal of Pharmaceutics*, 340(1–2), 126–133. <https://doi.org/10.1016/j.ijpharm.2007.03.011>
- Kayser, O. (2001). A new approach for targeting to *Cryptosporidium parvum* using mucoadhesive nanosuspensions: Research and applications. *International Journal of Pharmaceutics*, 214(1–2), 83–85. [https://doi.org/10.1016/S0378-5173\(00\)00640-2](https://doi.org/10.1016/S0378-5173(00)00640-2)
- Khan, M. R., & Rizvi, T. F. (2017). Application of nanofertilizer and nanopesticides for improvements in crop production and protection. In *Nanoscience and plant–soil systems* (pp. 405–427). https://doi.org/10.1007/9783319530570_14
- Kim, J., Park, Y., Yoon, T. H., Yoon, C. S., & Choi, K. (2010). Phototoxicity of CdSe/ZnSe quantum dots with surface coatings of 3-mercaptopropionic acid or tri-n-octylphosphine oxide/gum arabic in *Daphnia magna* under environmentally relevant UV-B light. *Aquatic Toxicology*, 97(2), 116–124. <https://doi.org/10.1016/j.aquatox.2009.12.022>
- Kim, D. Y., Kadam, A., Shinde, S., Saratale, R. G., Patra, J., & Ghodake, G. (2018). Recent developments in nanotechnology transforming the agricultural sector: A transition replete with opportunities. *Journal of the Science of Food and Agriculture*, 98(3), 849–864. <https://doi.org/10.1002/jsfa.8749>
- Krishna, M. S., Rai, P. K., & Bara, B. M. (2017). Studies on effect of polymer seed coating, nanoparticles and hydro priming on seedling characters of chickpea (*Cicer arietinum* L.) seed. *Journal of Pharmacognosy and Phytochemistry*, 6(4), 489–492.
- Kulizhskiy, S. P., Loiko, S. V., Morgalev, Y., Istigechev, G. I., Rodikova, A. V., & Maron, T. A. (2017). Investigation of platinum and nickel nanoparticles migration and accumulation in soils within the southeastern part of West Siberia. *Nano Hybrids and Composites*, 13, 115–122. <https://doi.org/10.4067/S071895162017005000016>
- Lindfors, L., Forssén, S., Skantze, P., Skantze, U., Zackrisson, A., & Olsson, U. (2006). Amorphous drug nanosuspensions. 2. Experimental determination of bulk monomer concentrations. *Langmuir*, 22(3), 911–916. <https://doi.org/10.1021/la052367t>
- Lindfors, L., Skantze, P., Skantze, U., Westergren, J., & Olsson, U. (2007). Amorphous drug nanosuspensions. 3. Particle dissolution and crystal growth. *Langmuir*, 23(19), 9866–9874. <https://doi.org/10.1021/la700811b>

- Liu, X., Feng, Z., Zhang, S., Zhang, J., Xiao, Q., & Wang, Y. (2006). Preparation and testing of cementing nanosubnano composites of slower controlled release of fertilizers. *Scientia Agricultura Sinica*, 39, 1598–1604. [https://doi.org/10.1016/S16712927\(06\)601132](https://doi.org/10.1016/S16712927(06)601132)
- Liversidge, G. G., & Conzentino, P. (1995). Drug particle size reduction for decreasing gastric irritancy and enhancing absorption of naproxen in rats. *International Journal of Pharmaceutics*, 125(2), 309–313. [https://doi.org/10.1016/0378-5173\(95\)00148-C](https://doi.org/10.1016/0378-5173(95)00148-C)
- Liversidge, G. G., & Cundy, K. C. (1995). Particle size reduction for improvement of oral bioavailability of hydrophobic drugs: I. Absolute oral bioavailability of nanocrystalline danazol in beagle dogs. *International Journal of Pharmaceutics*, 125(1), 91–97. [https://doi.org/10.1016/0378-5173\(95\)00122-Y](https://doi.org/10.1016/0378-5173(95)00122-Y)
- Losner-Goshen, D., Portnoy, V. H., Mayer, A. M., & Joel, D. M. (1998). Pectolytic activity by the haustorium of the parasitic plant *Orobancha* L. (*Orobanchaceae*) in host roots. *Annals of Botany*, 81(2), 319–326. <https://doi.org/10.1006/anbo.1997.0563>
- Lucia, A., Toloza, A. C., Fanucce, M., Fernandez Peña, L., Ortega, F., Rubio, R. G., et al. (2020). Nanoemulsions based on thymol-eugenol mixtures: Characterization, stability and larvicidal activity against *Aedes aegypti*. *Bulletin of Insectology*, 73, 15360.
- Ma, R., Levard, C., Judy, J. D., Unrine, J. M., Durenkamp, M., Martin, B., et al. (2014). Fate of zinc oxide and silver nanoparticles in a pilot wastewater treatment plant and in processed biosolids. *Environmental Science & Technology*, 48(1), 104–112. <https://doi.org/10.1021/es403646x>
- Ma, Y. F., Zhao, Y. Q., Zhou, Y. Y., Feng, H. Y., Gong, L. L., Zhang, M. Q., et al. (2024). Nanoparticle-delivered RNAi-based pesticide target screening for the rice pest white-backed planthopper and risk assessment for a natural predator. *Science of the Total Environment*, 926, 171286. <https://doi.org/10.1016/j.scitotenv.2024.171286>
- Malaikozhundan, B., Vaseeharan, B., Vijayakumar, S., & Thangaraj, M. P. (2017). *Bacillus thuringiensis* coated zinc oxide nanoparticle and its biopesticidal effects on the pulse beetle, *Callosobruchus maculatus*. *Journal of Photochemistry and Photobiology, B: Biology*, 174, 306–314. <https://doi.org/10.1016/j.jphotobiol.2017.08.014>
- Malik, A., Islam, S., Malik, M. A., Dar, Z. M., Masood, A., Shafi, S., Rashid, B., & Sidique, S. (2020). Agricultural development in Asia: Potential use of nanomaterials and nanotechnology. In M. Asaduzzaman & M. Afroz (Eds.), *Agricultural development in Asia* (pp. 167–169). *IntechOpen*. <https://doi.org/10.5772/intechopen.101142>
- Matranga, V., & Corsi, I. (2012). Toxic effects of engineered nanoparticles in the marine environment: Model organisms and molecular approaches. *Marine Environmental Research*, 76, 32–40. <https://doi.org/10.1016/j.marenvres.2012.01.006>
- Mishra, V., Bansal, K. K., Verma, A., Yadav, N., Thakur, S., Sudhakar, K., & Rosenholm, J. M. (2018). Solid lipid nanoparticles: Emerging colloidal nano drug delivery systems. *Pharmaceutics*, 10(4), 191. <https://doi.org/10.3390/pharmaceutics10040191>
- Mody, V. V., Cox, A., Shah, S., Singh, A., Bevins, W., & Parihar, H. (2014). Magnetic nanoparticle drug delivery systems for targeting tumor. *Applied Nanoscience*, 4, 385–392. <https://doi.org/10.1007/s13204-013-0216-y>
- Müller, R. H., & Jacobs, C. (2002). Buparvaquone mucoadhesive nanosuspension: Preparation, optimisation and long-term stability. *International Journal of Pharmaceutics*, 237(1–2), 151–161. [https://doi.org/10.1016/S0378-5173\(02\)00040-6](https://doi.org/10.1016/S0378-5173(02)00040-6)
- Mwaanga, P., Mbulwe, S., Shumbula, P., & Nyirenda, J. (2017). Investigating the toxicity of Cu, CuO and ZnO nanoparticles on earthworms in urban soils. *Journal of Pollution Effects & Control*, 5(3), 2–9. <https://doi.org/10.4176/23754397.1000195>
- Ntalli, N. G., & Caboni, P. (2012a). Botanical nematicides in the mediterranean basin. *Phytochemistry Reviews*, 11, 351–359. <https://doi.org/10.1007/s1110101292413>
- Ntalli, N. G., & Caboni, P. (2012b). Botanical nematicides: a review. *Journal of Agricultural and Food Chemistry*, 60(40), 9929–9940. <https://doi.org/10.1021/jf301749t>
- Ntalli, N., & Caboni, P. (2017). A review of isothiocyanates biofumigation activity on plant parasitic nematodes. *Phytochemistry Reviews*, 16, 827–834. <https://doi.org/10.1007/s111010169476y>

- Oliveira, H. C., Stolf-Moreira, R., Martinez, C. B. R., Grillo, R., de Jesus, M. B., & Fraceto, L. F. (2015). Nanoencapsulation enhances the post-emergence herbicidal activity of atrazine against mustard plants. *PLoS One*, 10(7), e0132971. <https://doi.org/10.1371/journal.pone.0132971>
- Ostiguy, C., Roberge, B., Woods, C., & Soucy, B. (2010). Engineered nanoparticles: Current knowledge about OHS risks and prevention measures. <https://collections.banq.qc.ca/ark:/52327/2048462>.
- Pereira, A. E. S., Sandoval-Herrera, I. E., Zavala-Betancourt, S. A., Oliveira, H. C., Ledezma-Pérez, A. S., Romero, J., & Fraceto, L. F. (2017). γ -Polyglutamic acid/chitosan nanoparticles for the plant growth regulator gibberellic acid: Characterization and evaluation of biological activity. *Carbohydrate Polymers*, 157, 1862–1873. <https://doi.org/10.1016/j.carbpol.2016.11.073>
- Pérez, S., la Farré, M., & Barceló, D. (2009). Analysis, behavior and ecotoxicity of carbon-based nanomaterials in the aquatic environment. *TrAC Trends in Analytical Chemistry*, 28(6), 820–832. <https://doi.org/10.1016/j.trac.2009.04.001>
- Pimentel, D. (1995). Amounts of pesticides reaching target pests: Environmental impacts and ethics. *Journal of Agricultural and Environmental Ethics*, 8, 17–29. <https://doi.org/10.1007/BF02286399>
- Pimentel, D. (2009). Pesticides and pest control. In *Integrated pest management: innovation-development process: Volume 1* (pp. 83–87). https://doi.org/10.1007/9781402089923_3
- Pittol, M., Tomacheski, D., Simões, D. N., Ribeiro, V. F., & Santana, R. M. C. (2017). Macroscopic effects of silver nanoparticles and titanium dioxide on edible plant growth. *Environmental Nanotechnology, Monitoring & Management*, 8, 127–133. <https://doi.org/10.1016/j.enmm.2017.05.002>
- Prasad, R., Kumar, V., Kumar, M., & Choudhary, D. K. (Eds.). (2019). Nanobiotechnology in bioformulations. : Springer International Publishing.. <https://doi.org/10.1007/9783030170615>.
- Rakibuzzaman, M., Rahul, S., Ifaz, M. I., Gani, O., & Uddin, A. J. (2018). Nano Technology in agriculture. *International Journal of Business, Social and Scientific Research*, 7(1), 6-9.<http://www.ijbssr.com/currentissueview/14013296>.
- Rawat, S., Pullagurala, V. L., Adisa, I. O., Wang, Y., Peralta-Video, J. R., & Gardea-Torresdey, J. L. (2018). Factors affecting fate and transport of engineered nanomaterials in terrestrial environments. *Current Opinion in Environmental Science & Health*, 6, 47–53. <https://doi.org/10.1016/j.coesh.2018.04.003>
- Romheld, V. (1999). Foliar nutrient application: Challenge and limits in crop production. In *Proceedings of the 2nd international workshop on foliar fertilization, April 4–10, 1999* (pp. 1–34).
- Rossi, M., Cubadda, F., Dini, L., Terranova, M. L., Aureli, F., Sorbo, A., & Passeri, D. (2014). Scientific basis of nanotechnology, implications for the food sector and future trends. *Trends in Food Science & Technology*, 40(2), 127–148. <https://doi.org/10.1016/j.tifs.2014.07.003>
- Rouhani, M., Samih, M. A., & Kalantari, S. (2012). Insecticide effect of silver and zinc nanoparticles against *Aphis nerii* Boyer De Fonscolombe (Hemiptera: Aphididae). *Chilean Journal of Agricultural Research*, 72(4), 590. <https://doi.org/10.4067/S071858392012000400020>
- Ruffo Roberto, S., Youssef, K., Hashim, A. F., & Ippolito, A. (2019). Nanomaterials as alternative control means against postharvest diseases in fruit crops. *Nanomaterials (Basel)*, 9(12), 1752. <https://doi.org/10.3390/nano9121752>
- Schwab, F., Zhai, G., Kern, M., Turner, A., Schnoor, J. L., & Wiesner, M. R. (2016). Barriers, pathways and processes for uptake, translocation and accumulation of nanomaterials in plants—critical review. *Nanotoxicology*, 10(3), 257–278. <https://doi.org/10.3109/17435390.2015.1048326>
- Scrinis, G., & Lyons, K. (2007). The emerging nano-corporate paradigm: Nanotechnology and the transformation of nature, food and Agri-food systems. *The International Journal of Sociology of Agriculture and Food*, 15(2), 22–44. <https://doi.org/10.48416/ijisaf.v15i2.293>

- Siegrist, M., Stampfli, N., Kastenholz, H., & Keller, C. (2008). Perceived risks and perceived benefits of different nanotechnology foods and nanotechnology food packaging. *Appetite*, 51(2), 283–290. <https://doi.org/10.1016/j.appet.2008.02.020>
- Sigfridsson, K., Forssén, S., Hölländer, P., Skantze, U., & de Verdier, J. (2007). A formulation comparison, using a solution and different nanosuspensions of a poorly soluble compound. *European Journal of Pharmaceutics and Biopharmaceutics*, 67(2), 540–547. <https://doi.org/10.1016/j.ejpb.2007.02.008>
- Singh, B. K., Delgado-Baquerizo, M., Egidi, E., Guirado, E., Leach, J. E., Liu, H., & Trivedi, P. (2023). Climate change impacts on plant pathogens, food security and paths forward. *Nature Reviews Microbiology*, 21(10), 640–656. <https://doi.org/10.1038/s41579-023-00900-7>
- Soko, W., Chimbari, M. J., & Mukaratirwa, S. (2015). Insecticide resistance in malaria-transmitting mosquitoes in Zimbabwe: A review. *Infectious Diseases of Poverty*, 4, 1–12. <https://doi.org/10.1186/s4024901500767>
- Stadler, T., Buteler, M., & Weaver, D. K. (2010). Novel use of nanostructured alumina as an insecticide. *Pest Management Science: formerly Pesticide Science*, 66(6), 577–579. <https://doi.org/10.1002/ps.1915>
- Steppuhn, A., Gase, K., Krock, B., Halitschke, R., & Baldwin, I. T. (2004). Nicotine's defensive function in nature. *PLoS Biology*, 2(8), e217. <https://doi.org/10.1371/journal.pbio.0020217>
- Tadros, T., Izquierdo, P., Esquena, J., & Solans, C. (2004). Formation and stability of nano-emulsions. *Advances in Colloid and Interface Science*, 108, 303–318. <https://doi.org/10.1016/j.cis.2003.10.023>
- Tao, X., Fortner, J. D., Zhang, B., He, Y., Chen, Y., & Hughes, J. B. (2009). Effects of aqueous stable fullerene nanocrystals (nC60) on *Daphnia magna*: Evaluation of sub-lethal reproductive responses and accumulation. *Chemosphere*, 77(11), 1482–1487. <https://doi.org/10.1016/j.chemosphere.2009.10.027>
- Teixeira, M., Alonso, M. J., Pinto, M. M., & Barbosa, C. M. (2005). Development and characterization of PLGA nanospheres and nanocapsules containing xanthone and 3-methoxyxanthone. *European Journal of Pharmaceutics and Biopharmaceutics*, 59(3), 491–500. <https://doi.org/10.1016/j.ejpb.2004.09.002>
- Trotel-Aziz, P., Couderchet, M., Vernet, G., & Aziz, A. (2006). Chitosan stimulates defense reactions in grapevine leaves and inhibits development of *Botrytis cinerea*. *European Journal of Plant Pathology*, 114, 405–413. <https://doi.org/10.1007/s10658-006-0005-5>
- Ulrichs, C., Mewis, I., & Goswami, A. (2005). *Crop diversification aiming nutritional security in West Bengal: Biotechnology of stinging capsules in nature's water-blooms* (pp. 1–18). Ann Tech Issue of State Agri Technologists Service Assoc.
- Verger, P. J., & Boobis, A. R. (2013). Reevaluate pesticides for food security and safety. *Science*, 341(6147), 717–718. <https://doi.org/10.1126/science.124157>
- Vijayreddy, D., Dutta, P., & Puzari, K. R. (2023). Nanotechnology in plant disease management. *Research Biotica*, 5(2), 56–62. <https://doi.org/10.54083/ResBio/5.2.2023/5662>
- Wang, H., Yang, R., Yang, Z., Qin, L., & Ding, X. (2016). Development and evaluation of a novel phytosynthesized pesticide: Deltamethrinloaded solid lipid nanoparticles. *Journal of Agricultural and Food Chemistry*, 64(18), 3629–3635.
- Wang, Z., Thavarajah, N., & Fernando, X. (2024). Exploring silica nanoparticles: A sustainable solution for pest control in Sri Lankan rice farming. *Technologies*, 12(11), 210. <https://doi.org/10.3390/technologies12110210>
- Worrall, E. A., Hamid, A., Mody, K. T., Mitter, N., & Pappu, H. R. (2018). Nanotechnology for plant disease management. *Agronomy*, 8(12), 285. <https://doi.org/10.3390/agronomy8120285>
- Wu, J., Chang, J., Liu, J., Huang, J., Song, Z., Xie, X., et al. (2023). Chitosan-based nanopesticides enhanced anti-fungal activity against strawberry anthracnose as “sugar-coated bombs”. *International Journal of Biological Macromolecules*, 253, 126947. <https://doi.org/10.1016/j.ijbiomac.2023.126947>

- Xu, Z. P., Stevenson, G. S., Lu, C. Q., Lu, G. Q., Bartlett, P. F., & Gray, P. P. (2006). Stable suspension of layered double hydroxide nanoparticles in aqueous solution. *Journal of the American Chemical Society*, 128(1), 36–37. <https://doi.org/10.1021/ja056652a>
- Yan, S., Ren, B. Y., & Shen, J. (2021). Nanoparticle-mediated double-stranded RNA delivery system: A promising approach for sustainable pest management. *Insect Science*, 28(1), 21–34. <https://doi.org/10.1111/1744-7917.12822>
- Yang, W., Peters, J. I., & Williams, R. O., III. (2008). Inhaled nanoparticles—A current review. *International Journal of Pharmaceutics*, 356(1–2), 239–247. <https://doi.org/10.1016/j.ijpharm.2008.02.011>
- Yang, Y., Qin, Z., Zeng, W., Yang, T., Cao, Y., Mei, C., & Kuang, Y. (2017). Toxicity assessment of nanoparticles in various systems and organs. *Nanotechnology Reviews*, 6(3), 279–289. <https://doi.org/10.1515/ntrev-2016-0047>
- Zahir, A. A., Bagavan, A., Kamaraj, C., Elango, G., & Rahuman, A. A. (2012). Efficacy of plant-mediated synthesized silver nanoparticles against *Sitophilus oryzae*. *Journal of Biopesticides*, 5, 95.
- Zhao, X., Cui, H., Wang, Y., Sun, C., Cui, B., & Zeng, Z. (2017). Development strategies and prospects of nano-based smart pesticide formulation. *Journal of Agricultural and Food Chemistry*, 66(26), 6504–6512. <https://doi.org/10.1021/acs.jafc.7b02004>

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