

NANOTECHNOLOGY: BOON FOR DISEASE MANAGEMENT IN DIFFERENT CROPS

Abstract

In a world grappling with the challenges of feeding a growing population and ensuring food security, the role of nanotechnology in plant disease management becomes increasingly significant. The integration of nanotechnology in agriculture has emerged as a revolutionary approach for enhancing plant disease management strategies. Nanotechnology, with its focus on manipulating materials at the nanoscale, presents a unique set of tools and strategies that can be harnessed to address the complexities of plant diseases. From targeted delivery of agrochemicals to the development of nanomaterial-based formulations, the possibilities are both exciting and diverse. As we delve into this chapter, we embark on a journey to understand how nanotechnology is reshaping the way we approach plant disease management, offering solutions that are not only effective but also environmentally conscious. This chapter delves into the intricate relationship between nanotechnology and plant health, highlighting the unprecedented opportunities and advancements it offers in combating various plant diseases. Additionally, the challenges and ethical considerations associated with the widespread adoption of nanotechnology in plant disease management are critically examined. Through a synthesis of current research and technological advancements, this chapter aims to provide readers with a nuanced understanding of the transformative potential of nanotechnology in revolutionizing plant disease management. As the agricultural landscape faces escalating challenges from emerging pathogens and environmental stresses, embracing nanotechnology offers a promising avenue for sustainable, efficient, and eco-friendly solutions to safeguard global food security.

Keywords: Crop health, Disease management, Nanoscale, Nanotechnology, Sustainable Practices.

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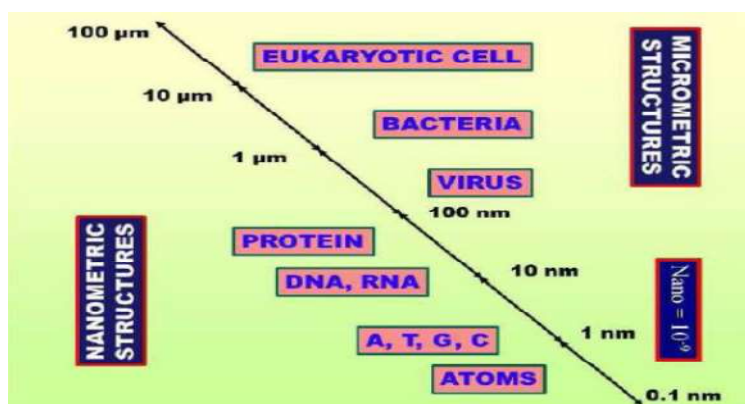
I. INTRODUCTION

Nanotechnology, conceived by Richard Feynman, represents the forefront of scientific exploration into materials that exhibit distinct attributes compared to their larger, macroscopic counterparts. Nano-materials possess the remarkable capability to operate on a molecular scale, manipulating atoms individually to assemble extensive structures with entirely novel molecular configurations. This intrinsic capacity underpins the diverse applications of nanotechnology, including its substantial impact on the realm of food production. The food industry has been greatly influenced by nanotechnology, contributing to the creation of fresh functional materials, innovative product design, and the establishment of methodologies and instruments for ensuring food safety and bio-security (Moraru *et al.*, 2003). As defined by the National Science Foundation (NSF) and the National Nanotechnology Initiative (NNI), nanotechnology involves the understanding, control, and manipulation of materials at the atomic and molecular levels, including the supramolecular level, which encompasses molecular clusters ranging in size from 0.1 to 100 nanometers. The ultimate objective is the fabrication of materials, devices, and systems boasting entirely novel properties and functionalities attributable to their diminutive structural dimensions. This field embodies the manipulation and exploitation of materials, device systems, and matter properties at the nanoscale, as established by researchers such as Ajayan *et al.* (2003) and Astruc *et al.* (2010). Nanotechnology transcends disciplinary boundaries, drawing from physics, chemistry, biology, material science, and engineering, as evidenced by its interdisciplinary nature highlighted by Roco (2007). Centering on the distinct properties arising from nanometric proportions, nanotechnology holds immense potential for transformative impacts across domains including agriculture, food production, biomedicine, environmental engineering, water resource management, energy conversion, and many more. The United States Department of Agriculture (USDA) first began addressing the incorporation of nanotechnology into agriculture and the food industry in 2003. Its utilization spans various areas, including disease management, precise pesticide release, the creation of diagnostic instruments, and the design of functional food systems. This involves the creation of interactive, edible nanopackaging to deter pathogens, precision release of chemicals, comprehensive nanoscale surveillance, and the design of interactive agrochemicals functioning as herbicides and pesticides. Consequently, nanotechnology emerges as a promising avenue for combating plant diseases through precise delivery of functional molecules or serving as a diagnostic tool for disease detection, as elucidated by Tarafdar and Raliya (2012). The novel realm of nanotechnology, characterized by its distinct material properties compared to their macroscopic counterparts, holds substantial potential across diverse fields. Central to nanotechnology's essence is its ability to manipulate matter at the molecular scale, atom by atom, culminating in the assembly of extensive structures with unprecedented molecular arrangements. The overarching goal is to harness these distinctive properties by acquiring mastery over structures and devices at atomic, molecular, and supramolecular tiers, optimizing their efficient production and utilization. Nanotechnology has ushered in innovative solutions for challenges within plant science and food technology, particularly in post-harvest product preservation, while also presenting novel methodologies for raw material selection and processing, ultimately enhancing the quality of plant-based products. At the heart of nanotechnology lies the capability to condense tools and devices within the nanometer range, accumulating atoms and molecules into more substantial structures while maintaining their diminutive size.

1. Properties of Nanoparticles: Nanoparticles exhibit distinct properties that sharply contrast with their bulk counterparts, and these properties are harnessed for their applications in nanotechnology. These properties include:

- **Small Size (1-100nm):** Nanoparticles possess dimensions within the range of 1 to 100 nanometers.
- **High Surface-to-Volume Ratio:** Nanoparticles boast an expansive surface area relative to their volume.
- **Modifiable Chemical and Physical Properties:** The chemical and physical attributes of nanoparticles can be altered.
- **Size- and Shape-Dependent Changes:** Nanoparticles exhibit variations in chemical and physical properties based on their size and shape.
- **Structural Resilience despite Atomic Composition:** Nanoparticles maintain structural integrity despite being composed of individual atoms.
- **Enhanced or Delayed Particle Aggregation:** Surface modifications have a significant impact on how nanoparticles tend to aggregate. These changes lead to heightened photoemission, improved electrical and thermal conductivity, and enhanced surface catalytic activity. (Roco, 2007).

Nanostructures can exist in various dimensional forms, which include zero-dimensional (referred to as nanoparticles), 1-dimensional (referred to as nanowires), 2-dimensional (such as thin films), and 3-dimensional configurations (like arrays and hierarchical structures). Figure 1 offers a visual comparison of different nano and microstructures found in biology.



Source: Misraet *al.*, 2013

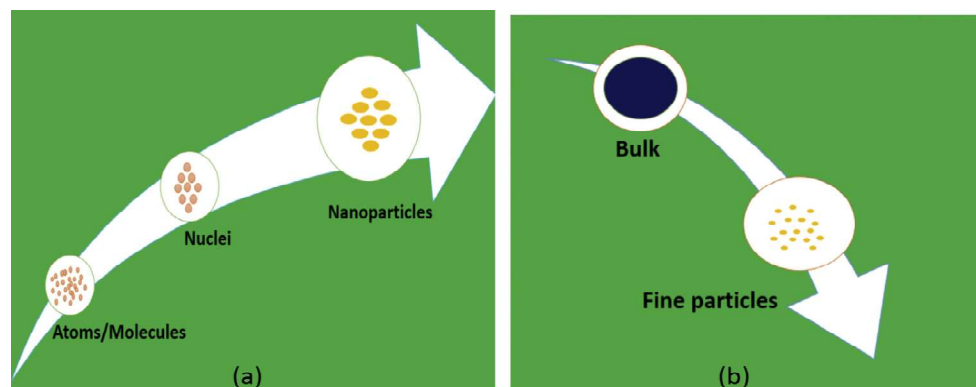
Figure 1: Illustration of scale that showcases the dimensions of various nanometre and micrometre-sized objects found in biological materials, with 'A,' 'T,' 'G,' and 'C' representing nucleotide molecules.

2. Techniques for Nanoparticle Preparation: Nanomaterials are prevalent in nature, as biological organisms inherently operate on the nanoscale. Nanotechnologists aim to produce and employ both novel synthetic nanomaterials and certain naturally occurring nanomaterials on a larger scale and with greater uniformity in size. A range of techniques are employed to synthesize diverse nanomaterials. Nanostructures can be generated

through two distinct methodologies commonly known as the top-down process and the bottom-up process.

The top-down approach typically involves the disintegration of larger material entities (either physically or chemically) into smaller units possessing desired shapes and dimensions. This is achieved through techniques such as mechanical milling and ion implantation, among others.

In contrast, the bottom-up approach employs self-assembly as a mechanism to construct nanostructures by precisely arranging individual atoms and molecules together. This approach is illustrated in Figure 2.



Source: Shakeelet *al.*, 2015

Figure 2: Bottom up (a) and top down (b) process.

Various Methods for Nanoparticle Preparation:

- **Solvent Extraction/Evaporation:** Nanoparticles composed of particular organic polymers can be produced via a method that includes dissolving the polymers in a solvent, followed by subjecting them to sonication, evaporation, filtration, and ultimately freeze-drying. This method has been employed, for instance, in the creation of polymer nanoparticles using dichloromethane as a solvent (Zhang and Feng, 2006).
- **Crystallization:** The formation of nanoparticles can also occur via the crystallization process. In one example, hydroxyapatite-aspartic acid (or glutamic acid) crystals were generated by introducing varying concentrations of amino acids into solution (Boaniniet *al.*, 2006).
- **Self-Assembly:** Manipulating factors like pH, temperature, and solute concentrations can induce the self-assembly of molecules, resulting in the formation of fibrous nanostructures. This technique has been employed to create vesicles referred to as polymerosomes, which can encapsulate substances. Polymerosomes are self-assembled through the gradual evaporation of an organic solvent (Lorencauet *al.*, 2005).
- **Layer-by-Layer Deposition:** Layer-by-layer deposition involves the sequential application of layers of different materials. As an example, platforms that can accommodate bilayer membranes, ideal for protein analysis, can be manufactured by initially applying sodium silicate and poly ally amine hydrochloride onto a gold

substrate, followed by a calcination process. Subsequently, lipid bilayers can seamlessly merge with the silicate layer, enabling the detection of particular proteins, as described by Phillips *et al.* in 2006..

- **Microbial Synthesis:** Living cells, including fungi and bacteria, can be harnessed to generate nanoparticles. For example, extracellular synthesis of silver nanoparticles has been achieved using the fungus *Aspergillus fumigatus*. Various other fungi and bacterial species have also been employed for producing gold and silver nanoparticles (Bhainsa and D'Souza, 2006; Bhattacharya and Gupta, 2005).

II. RELEVANCE OF NANOTECHNOLOGY TO PLANT PATHOLOGY

The intersection of nanotechnology and plant pathology holds substantial significance. Nanotechnology offers innovative tools for disease control, such as the controlled delivery of functional molecules and enhanced disease detection. Additionally, it enables the development of nano-encapsulated agrochemicals, interactive nano wrappers to counter pathogens, and novel diagnostic tools. This convergence has the potential to revolutionize agriculture and address challenges related to plant diseases, while also impacting various other sectors through the unique properties and functionalities of nanomaterials.

1. **Detection and Diagnosis of Plant Pathogens:** The early identification of plant diseases has spurred the exploration of nanotechnology-based solutions to safeguard food and agriculture against bacterial, fungal, and viral agents. Researchers are envisioning the integration of autonomous nanosensors with GPS systems for real-time field monitoring, encompassing both soil conditions and crop health. By combining biotechnology and nanotechnology in sensor development, more sensitive equipment can be created, enabling faster responses to environmental changes and disease outbreaks. There is a pressing need for highly sensitive diagnostic instruments capable of swiftly identifying molecular irregularities, whether at the genomic or biochemical level. In biological systems, functional nanoscale devices such as enzymes, proteins, and nucleic acids occur naturally and are pivotal in monitoring essential plant processes. The diagnosis of diseases poses a significant challenge due to the exceedingly low concentrations of biochemical substances and the limited quantities of detectable viruses, fungi, or bacterial infections, as discussed by Misra *et al.* in 2013.
2. **Nanosized Metals as Diagnostic Probes:** While current diagnostic methods for detecting plant pathogens are still in their early stages and not yet perfected, researchers are actively exploring ways to harness the advantages of nanomaterials to overcome the limitations of existing diagnostic tools. Nanoparticles, when reduced to nanoscale dimensions (1-100 nm), possess unique properties that make them valuable for use as diagnostic probes, as discussed by Sharon *et al.* in 2010. One promising approach involves the use of fluorescent silica nanoprobe for rapid plant disease diagnosis. These nanoprobe, when combined with the secondary antibody of goat anti-rabbit IgG, were employed to detect the bacterial plant pathogen *Xanthomonas axonopodis* sp. *Vesicatoria*, responsible for causing bacterial spot disease in solanaceous plants. The fluorescent silica nanoprobe, integrated with the organic dye tris-2,2'-bipyridyl dichloro ruthenium (II) hexahydrate (Rubpy), emitted fluorescence and exhibited photostability, rendering them well-suited for diagnostic purposes, as reported by Yao *et al.* in 2009.

III. NANOSCALE BIOSENSORS/NANOSENSORS

The development of small, portable nanosensors holds the potential for rapid, real-time, accurate, quantitative, reliable, and stable disease detection. Detecting infections in asymptomatic plants and subsequently delivering targeted treatments are vital components of precision farming. Nugaeva *et al.* (2005) demonstrated the use of micromechanical cantilever arrays for detecting fungal spores (*Aspergillus niger* and *Saccharomyces cerevisiae*). Functional proteins such as concanavalin A, fibronectin, or immunoglobulin G were grafted onto micro-fabricated silicon cantilevers, both uncoated and gold-coated. The cantilevers responded to the molecular structures on fungal cell surfaces, causing a shift in resonance frequency that was measured by dynamically operated arrays. This approach provided results in a matter of hours compared to several days using conventional methods. The shift in frequency was proportional to the mass of a single fungal spore, enabling quantitative estimation. The biosensors detected target fungi in the range of 10^3 - 10^6 cfu ml⁻¹ (Nugaeva *et al.*, 2005).

IV. QUANTUM DOTS (QDs)

Quantum dots are fluorescent, crystalline semiconductor particles with diameters in the range of a few nanometers. These dots confine excitons in all three spatial dimensions. QDs have emerged as important tools for detecting specific biological markers with high accuracy, finding applications in cell labeling, tracking, in vivo imaging, and DNA detection (Sharon *et al.*, 2010).

V. MANAGEMENT OF PLANT DISEASES USING NANOPARTICLES

Nanotechnology is emerging as a potential solution for managing plant diseases, with nanoparticles of carbon, silver, silica, and alumino-silicates gaining attention. Carbon nanotubes (CNTs), for instance, have shown promise by not only penetrating the hard coats of germinating tomato seeds but also enhancing their growth. This growth promotion is attributed to increased water uptake facilitated by CNT penetration. CNTs could potentially serve as vehicles to deliver beneficial molecules during germination to protect seeds from diseases, as their growth-promoting nature poses no harm to plants. Several bacterial and fungal pathogens negatively impact vegetables, including *Erwinia carotovora*, *Pseudomonas* spp., *Corynebacterium*, *Xanthomonas campestris*, *Alternaria*, *Aspergillus*, *Cladosporium*, *Colletotrichum*, *Fusarium*, and more. These pathogens lead to economic losses, and some even produce toxic metabolites affecting human health. Addressing the challenges posed by an estimated doubling of global food demand in the next 50 years is essential.

Nanotechnology provides potential solutions for crop protection, including the controlled release of encapsulated pesticides and fertilizers, as well as early disease detection through nanosensors. Utilizing nanomaterials in crop protection offers efficient approaches to manage plant pathogens. Several nanoparticles are employed in plant disease management:

- 1. Biopolymer Nanoparticles:** Developing nanoformulations for agrochemicals requires biodegradable, nontoxic, eco-friendly, and cost-effective materials. Biopolymers derived from natural sources fulfill these requirements and serve as an attractive alternative to petrochemical-based nanomaterials.

2. **Chitosan:** Chitosan nanoparticles find multiple applications due to their biodegradability and non-toxic nature. Under acidic conditions, chitosan's free amino groups become positively charged, contributing to its effectiveness. Chitosan combats fungi through several mechanisms:

- Interaction with fungal membrane components, altering membrane permeability and leading to cell death.
- Chelation with metal ions, disrupting fungal growth by depriving them of essential nutrients.
- Penetration of fungal cell walls, binding to DNA, and inhibiting protein and enzyme synthesis.

Chitosan and chitosan nanoparticles have demonstrated effectiveness against plant pathogens like *Fusariumsolani*, with particle size and zeta potential influencing their inhibitory effects. The use of low molecular weight chitosan nanoparticles with varying sizes exhibited antibacterial activity, highlighting the significance of zeta potential in binding to microbial membranes. The antimicrobial activities of chitosan, its derivatives, bound metal ions, and nanoparticles have been widely studied (Sanpuiet *al.*, 2008; Jagadishet *al.*, 2012; Kaur *et al.*, 2012) (Figure 3).

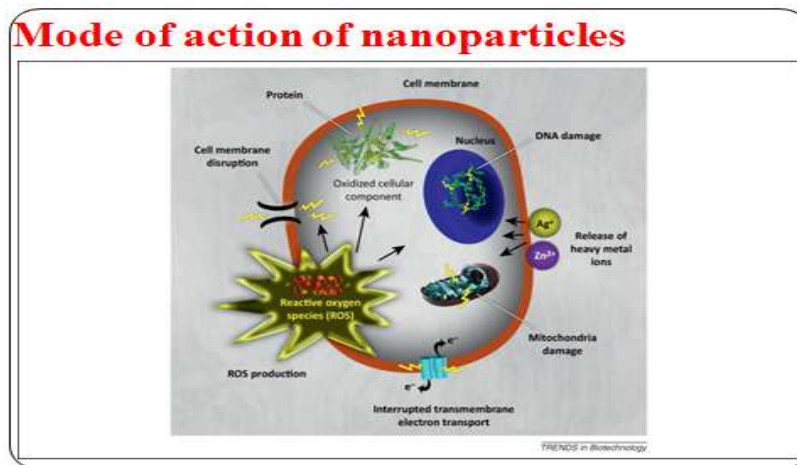


Figure 3: Mode of action of nanoparticles.

3. **Metallic Nanoparticles:** Metallic nanoparticles possess unique chemical and physical characteristics due to their small size, substantial surface-to-volume ratio, structural stability, and strong binding affinity for specific targets, as highlighted by Kumar *et al.* in 2010. These nanoparticles present a promising approach as innovative antimicrobial agents, offering an alternative to synthetic fungicides for inhibiting or suppressing the growth of diverse pathogens. The effectiveness of metallic nanoparticles arises from their capacity to employ multiple modes of inhibition.
4. **Carbon Nanoparticles:** Recent scientific studies have highlighted the potential benefits of using carbon nanotubes (CNTs) to enhance plant growth and protect against diseases. In a notable experiment, tomato seeds were planted in soil containing CNTs, which not only penetrated the tough coat of germinating seeds but also exhibited growth-enhancing

effects. This growth enhancement is attributed to the increased water uptake resulting from CNT penetration. The ability of CNTs to promote growth without toxicity makes them an attractive option for delivering protective molecules to seeds during germination. It's worth noting that high concentrations of carbon nanomaterials (CNMs) might obstruct water channels and potentially hinder water uptake and spore development, leading to plasmolysis.

There is speculation that Carbon Nanomaterials (CNMs) could potentially affect the gating of existing water channels known as aquaporins in spores, potentially disrupting biological pathways before spore development. While certain water channel genes, including the critical *LeAqp2* gene in tomato plants, were affected by multi-walled carbon nanotubes (MWCNTs), it's important to note that spore-specific water channel aquaporins (*Aqp1*) were produced during the later stages of sporulation. This suggests that CNMs may not directly regulate the expression of aquaporins. Consequently, the influence of CNMs on spore water uptake, particularly when they block it due to the adsorption of CNMs on the surface, could be a significant factor contributing to plasmolysis and the inhibition of spore germination.

In experiments, when subject to the highest dose of SWCNTs (500 $\mu\text{g/mL}$), spore germination of the fungus was inhibited by over 90.8%. Similarly, MWCNTs, GO (graphene oxide), and rGO (reduced graphene oxide) also exhibited inhibitory effects on spore germination, although to varying degrees. C60 and AC (activated carbon), on the other hand, showed no significant difference from the control conditions in terms of their effects on the spore germination of the fungus.

5. **Nano Alumino-Silicate:** Leading chemical companies are exploring nanoscale formulations of efficient pesticides, including the use of Alumino-Silicate nanotubes with active ingredients. These nanotubes offer an advantage: when sprayed on plant surfaces, they are readily picked up by insect hairs. Insects that groom themselves inadvertently consume these pesticide-loaded nanotubes. This method offers biologically more active and environmentally safer alternatives to traditional pesticides. Mesoporous Silica Nanoparticles have been investigated for their ability to deliver DNA and chemicals into plants, introducing a powerful tool for targeted delivery into plant cells. Spherical nanoparticles with independent porous channels have been developed, featuring a honeycomb-like structure capable of holding chemicals or molecules (Wang *et al.*, 2002). These nanoparticles possess a unique "capping" strategy that keeps the contents sealed until activated to release their cargo inside plant cells, providing precise control over timing. These nanoparticles have been employed successfully to introduce DNA and chemicals into various plant species, including arabidopsis, tobacco, and corn. Another advantage is their capability to deliver multiple biogenic species simultaneously.
6. **Silver Nanoparticles:** Plant diseases continue to hinder agricultural production worldwide, leading to significant financial losses spent on disease control measures. While pesticides are commonly used, the environmental risks and residues associated with their application have prompted the search for alternative methods. Silver nanoparticles have garnered significant interest as antimicrobial agents, primarily because they hold the potential to provide a more environmentally friendly solution, as noted by Jo *et al.* in 2009 and Kim *et al.* in 2012. Silver has a historical record of use for its antimicrobial properties, dating back to ancient times, and it is favored for its wide-

ranging effectiveness and multiple mechanisms of action against microorganisms, as highlighted by Wei *et al.* in 2009. Silver demonstrates higher toxicity to microorganisms while maintaining lower toxicity to mammalian cells. The adoption of silver nanoparticles as antimicrobial agents is further fueled by their cost-effective production and their ability to inhibit microorganisms in various ways, as discussed by Clement and Jarrett in 1994. Among various nanoparticles, silver nanoparticles stand out due to their strong inhibitory and antimicrobial activities.

Nano silver colloid represents a finely dispersed and stabilized solution containing silver nanoparticles, which exhibit enhanced adhesion to bacterial and fungal surfaces, rendering them more effective as fungicides. This formulation proves effective in eradicating undesired microorganisms in both soil used for planting and hydroponic systems. It is also employed as a foliar spray to counteract mold, decay, and various plant diseases. Additionally, silver demonstrates its capacity as a catalyst for plant growth. The wide spectrum of applications for this nearly odorless, nearly tasteless, and colorless disinfectant and healing agent encompasses numerous indispensable functions. A composite known as Nano Silica-Silver emerges as a combination of silicon (Si) absorbed into plants to heighten their resilience to diseases and environmental stressors. The aqueous silicate solution applied to plants is recognized for its capacity to preemptively combat pathogenic microorganisms that give rise to conditions like powdery mildew or downy mildew in plants. This solution also supports enhanced physiological activity and growth in plants, fostering resistance to disease and stress. Nonetheless, while silica demonstrates these beneficial traits, it does not directly exhibit disinfection capabilities against established plant pathogens. The efficacy of silica is influenced by the specific physiological context, making it ineligible for registration as an agricultural chemical. In the realm of disinfection, silver's prowess is widely acknowledged. Its mechanism of action involves deactivating enzymes integral to the metabolic functions of unicellular microorganisms through a process known as oligodynamication. This attribute extends to inhibiting the proliferation of algae. When existing as ionic silver, its antimicrobial activity is remarkably potent. However, the reactivity of ionic silver renders it susceptible to oxidation or reduction, transforming it into a metallic form contingent upon its surrounding environment. This transition does not sustain continuous antimicrobial efficacy. In contrast, silver in the form of metal or oxide exhibits stability within the environment. However, its limited antimicrobial activity necessitates its usage in relatively higher quantities, which is not an optimal approach. A novel formulation consisting of nano-sized Silica Silver has been developed to address a range of plant diseases. This composition combines nano-silver with silica molecules and a water-soluble polymer, created through exposure to radioactive rays. In practical tests conducted in both field and greenhouse settings, the solution demonstrated antifungal properties and effectively controlled powdery mildew in pumpkins at a concentration of 0.3 ppm. Within three days of application, the infected leaves exhibited the disappearance of pathogens, leading to sustained plant health. Exploration of the effective concentration of nanosized silica-silver was undertaken to gauge its impact on the growth inhibition of various fungi. Notably, *Pythiummultimum*, *Magnaportheorisea*, *Colletotrichumgloeosporioides*, *Botrytis cinerea*, and *Rhizoctoniasolani* demonstrated complete growth inhibition at a concentration of 10 ppm of the nanosized silica-silver. Previous research has shown that silver ions (Ag⁺) have inhibitory effects on microorganisms by interfering with DNA replication, resulting in the deactivation of essential cellular proteins and enzymes needed for ATP production. In a study conducted

by Kim *et al.* in 2008, the effectiveness of colloidal nano-silver solutions in combating rose powdery mildew was assessed. Nano-silver colloids have improved adhesion to the surfaces of bacterial and fungal cells, making them more effective fungicides due to their well-dispersed and stable silver nanoparticle solution. Notably, nano silver falls under the classification of a pesticide (Anwar *et al.*, 2008, Baier, 2009). Given silver's exceptional antimicrobial properties, it has gained acceptance as a replacement for traditional agrochemicals. Furthermore, it serves as a plant-growth stimulator and contributes to the reduction of undesired microorganisms in both soil and hydroponic systems (Sharma *et al.*, 2012). Although relatively few studies have addressed the use of silver for controlling diverse plant pathogens in a safer manner compared to synthetic fungicides (Park *et al.*, 2006), nanoparticles, such as silver nanoparticles, offer efficient penetration into microbial cells. This enables the achievement of effective microbial control at lower concentrations. This is especially relevant for microorganisms that demonstrate reduced sensitivity to antibiotics due to limited antibiotic penetration into microbial cells (Samuel and Guggenbichler, 2004). Lamsalet *et al.* (2011a) showcased the effective utility of silver nanoparticles as an alternative to commercial fungicides. The fungistatic activity of silver nanoparticles on fungi is found to be dose-dependent (Jo *et al.*, 2009, Aguilar-Méndez *et al.*, 2011, Lamsalet *et al.*, 2011b, Kim *et al.*, 2012). Investigations into the effects of silver nanoparticles on the growth of sclerotium-forming species, including *Rhizoctoniasolani*, *Sclerotiniasclerotiorum*, and *S. minor*, revealed a dose-dependent inhibition of hyphal growth. Microscopic observation of hyphae exposed to silver nanoparticles displayed severe damage, leading to the separation of hyphal wall layers and collapse of fungal hyphae (Bhat *et al.*, 2009, Min *et al.*, 2009).

7. **Silica Nanoparticles:** Silicon (Si) has gained recognition for its ability to improve disease resistance and stress tolerance in plants, as noted by Brecht *et al.* in 2004. Additionally, it plays a role in stimulating various physiological processes and overall plant growth, as discussed by Carver *et al.* in 1998. Torney *et al.* in 2007 investigated the use of honeycomb mesoporous silica nanoparticles (MSN) with 3nm pores as a delivery system for introducing DNA and chemicals into plant cells and leaves. Their method involved loading the target gene and its chemical activator into the MSN structure, sealing the ends with gold nanoparticles, and examining the controlled release of chemicals and the subsequent induction of gene expression in plants. This research showcased the potential of silica nanoparticles for precise delivery of proteins, nucleotides, and chemicals in the context of plant biotechnology. Silicon (Si) absorption by plants has been linked to bolstered disease resistance and stress resilience, attributed to its promotion of physiological activity and growth. Aqueous solutions containing silicate have exhibited remarkable preventive effects against pathogenic microorganisms that trigger conditions such as powdery mildew and downy mildew in plants. Additionally, these solutions have shown promise in enhancing overall plant physiological activity and growth, thereby fostering disease and stress resistance.
8. **Copper Nanoparticles:** Copper-based fungicides are known to generate highly reactive hydroxyl radicals, which possess the ability to impair lipids, proteins, DNA, and various other biomolecules. This mechanism underpins their crucial role in preventing and treating a diverse array of plant diseases (Borkow and Gabbay, 2005). The integration of copper with chitosan nanogels has exhibited a potent synergistic outcome between chitosan and copper, effectively inhibiting the growth of the phytopathogenic fungus *Fusariumgraminearum*. The biocompatibility of these nanohydrogels positions them as a

promising copper-based bio-pesticide generation, offering potential for their utilization as an effective delivery platform for copper-centered fungicides aimed at safeguarding plants (Brunel *et al.*, 2013). Incorporating copper nanoparticles into low melting point soda-lime glass powder has demonstrated noteworthy antimicrobial effectiveness against a spectrum of microorganisms including gram-positive and gram-negative bacteria, yeast, and fungi. The enhanced antimicrobial action is attributed to the inhibitory synergistic impact of Ca^{2+} ions released from the glass (Esteban-Tejeda *et al.*, 2009).

9. **Zinc Nanoparticles:** The mode of action of nano-ZnO derived from zinc nitrate against the notable fungal pathogen *Aspergillus fumigatus* has been elucidated, revealing a process involving hydroxyl and superoxide radicals. This interaction results in cell wall distortion and subsequent demise of the fungus due to the transfer of high energy (Patra and Goswami, 2012). Zinc oxide nanoparticles (ZnO NPs) have displayed potential as effective fungicides in both agricultural and food safety contexts. A recent investigation by Heet *et al.* (2011) showcased notable inhibition of two post-harvest pathogenic fungi, *Botrytis cinerea* and *Penicillium expansum*, through the utilization of ZnO NPs measuring approximately 70 nm in size and at lower concentrations. The mechanism of action was confirmed through scanning electron microscopy (SEM) and Raman spectroscopy. ZnO nanoparticles induce morphological changes in fungal hyphae, hinder conidiophore and conidial development, ultimately culminating in the demise of the fungal hyphae.
10. **Nano Composites:** Although silver has predominantly been studied for its antibacterial properties, its potential as an antifungal agent is gaining recognition. Pinto *et al.* in 2013 investigated the preparation and antifungal capabilities of composite films made from pullulan and silver nanoparticles (Ag NPs) using *Aspergillus niger* as a model organism. Their research demonstrated that these composite films possess strong inhibitory effects on fungal sporulation, which was further confirmed through scanning electron microscope (SEM) visualization of disrupted spore cells. It's worth noting that silver, when in an ionic state, exhibits heightened antimicrobial activity, as discussed by Thomas and McCubbin in 2003. In the context of plant disease management, Park *et al.* in 2006 introduced a novel nano-sized Silica-Silver composite with promising antifungal properties. The composite demonstrated significant antifungal efficacy, causing pathogenic disappearance from infected leaves within three days of application and ensuring plant health thereafter. The researchers endeavored to ascertain the optimal concentration of these composites, effectively suppressing the growth of numerous pathogens like *Pythium multivium*, *Magnaporthe grisea*, *Bacillus subtilis*, and *Xanthomonas campestris* sp. *Vesicatoria*. Park *et al.* (2006) conducted tests using nanosized silica-silver (Si-Ag) particles against various fungal and bacterial pathogens. In vitro experiments indicated that silica-silver nanoparticles exhibited higher efficacy against fungi at a dosage of 10 ppm, causing complete inhibition of vegetative growth.

VI. NANOPARTICLES IN POST-HARVEST DISEASE MANAGEMENT

The escalating global population, diminishing natural resources, and the emergence of resilient pathogens have rendered the provision of ample and wholesome food a formidable challenge. This predicament is poised to intensify manifold in the near future. Consequently, the imperative to augment production efficiency and curtail post-harvest losses has arisen, necessitating the deployment of progressive technologies like biotechnology and nanotechnology in the realm of post-harvest products. Nanotechnology has been notably

harnessed in the agricultural and horticultural sectors, contributing to prolonged shelf life, regulation of microorganism proliferation through nanofilms and coatings, attenuation of gas influence and detrimental UV rays, and the utilization of Nano biosensors to detect quality and spoilage indicators (Yadollahiet *al.*, 2009). Nanotechnology's potential encompasses post-harvest operations such as drying, storage, and preservation of agricultural commodities. Chitosan, an enzymatically deacetylated derivative of chitin, emerges as an efficacious agent in mitigating post-harvest deterioration of fruits and vegetables (Liu *et al.*, 2007). The application of chitosan at 1 g/L has demonstrated significant efficacy in curtailing the proliferation of diverse phytopathogenic fungi responsible for post-harvest spoilage (Hirano, 1997, Liu *et al.*, 2009, Yu *et al.*, 2012, Shi *et al.*, 2013). Subsequent research extensively studied the post-harvest treatment potential of nanosilver (Lu *et al.*, 2010; Li *et al.*, 2012; Liu *et al.*, 2012; Mohsen Kazemi., 2012; Nazemi Rafi and Ramezani, 2013). The potential of nanomaterials bears profound implications for post-harvest disease management, with research findings underscoring their superior applicability and advantages over conventional packing materials in safeguarding the physicochemical and physiological quality of stored fruits, vegetables, and other horticultural produce.

1. Nanostructures in Association - Colloidal Forms for Functional Ingredient Delivery:

Nanostructures, including surfactant micelles, vesicles, bilayers, reverse micelles, and liquid crystals, have emerged as highly suitable nanomaterials for facilitating the dispersion and encapsulation of functional ingredients. In colloidal systems, small particles are stably distributed within a liquid medium. Association colloids have been widely used to transport functional ingredients with different polarities, including polar, non-polar, and amphiphilic compounds (references 21-24). The nanoparticle sizes typically found in colloids range from 5 to 100 nm. However, a notable drawback of colloids is their tendency to spontaneously break apart upon dilution.

2. Nano-Emulsions: Nano-emulsions, consisting of two or more liquids that do not naturally mix, such as oil and water, are defined by their limited ability to blend together. In nano-emulsions, the individual droplets have diameters of 500 nm or smaller. These nano-emulsions possess the capability to encapsulate functional ingredients within their tiny droplets, which helps minimize chemical degradation.

3. Nanoparticles as Intelligent Delivery Systems: Syngenta, a prominent agricultural company, has harnessed the potential of nanoemulsions in their growth regulator, Primo MAXX®. This innovative approach involves applying the product prior to stress triggers like heat, drought, disease, or traffic. By doing so, the physical resilience of turfgrass is enhanced, enabling it to endure various stressors throughout the entire growth season. Another product from Syngenta, Karate® ZEON, utilizes encapsulation to deliver a wide-ranging spectrum of pesticides. Upon contact with leaves, the encapsulated structure breaks open, releasing the active compounds. Notably, the encapsulated product "gutbuster" responds to alkaline environments, selectively releasing its contents upon encountering such conditions. The ultimate goal is to customize these products for controlled release in response to diverse cues, such as magnetic fields, heat, ultrasound, moisture, and more. Ongoing research also aims to enhance plant efficiency in utilizing water, pesticides, and fertilizers, thereby reducing pollution and promoting environmentally-friendly agricultural practices.

VII. ROLE OF PLANT PATHOGENS IN NANOPARTICLE BIOSYNTHESIS

Nanoscience and nanotechnology research involve the development and application of nanoparticles composed of a wide range of elements and compounds. Among their many uses, nanoparticles are increasingly recognized for their potential as antimicrobial agents in the management of plant diseases. Nanoparticles can be produced using various methods, either through physical or chemical processes. A particularly safe method for nanoparticle production is through biological systems, with microorganisms being a notable example, as discussed by Mansoori in 2005. Microorganisms offer numerous benefits in this context, including: i) tailored outcomes achievable through biotechnology, ii) ease of manipulation, particularly with fungi (Vigneshwaran *et al.*, 2006), iii) cost-effectiveness, iv) potential for scalable production, v) high efficiency (Goodsell, 2004), vi) simplicity, and vii) alignment with green chemistry or eco-friendliness. Microorganisms have been recognized as "biofactories" for generating metallic nanoparticles.

- Fungi:** The utilization of fungi for nanoparticle synthesis is a relatively recent trend. A transition from bacteria to fungi as natural "nanofactories" has been observed due to advantages like straightforward downstream processing, ease of handling (Mandalet *et al.*, 2006), and their capacity to secrete substantial quantities of enzymes. Nevertheless, fungi, being eukaryotic organisms, are less amenable to genetic manipulation compared to prokaryotes. Thus, genetically modifying fungi for enhanced nanoparticle synthesis might present challenges. Several fungi have been explored for their ability to synthesize metallic nanoparticles, with diverse outcomes in terms of shape, size, and other material properties (Table 1). Understanding the mechanisms of nanoparticle synthesis within microbial systems is crucial for exerting control over the desired characteristics of the resulting nanomaterials.
- Bacteria:** Among microorganisms, prokaryotes have been at the forefront of attention for nanoparticle biosynthesis (Mandalet *et al.*, 2006), as evidenced by examples presented in Table 1. Bacteria have been harnessed for the biosynthesis of various nanoparticles, including silver, gold, FeS, magnetite, and quantum dots like cadmium sulphide (CdS), zinc sulphide (ZnS), and lead sulphide (PbS).

Table 1: Nanoparticles Synthesized by Fungi and Bacteria.

S.No.	Nanoparticle	Fungus	Reference
1	Silver nanoparticles	<i>Verticillium</i> sp	Sastry <i>et al.</i> 2003
2		<i>Phoma</i> sp.	Chen <i>et al.</i> 2003
3		<i>F. oxysporum</i>	Duran <i>et al.</i> , 2005
4		<i>Phaenerochaete chrysosporium</i>	Vigneshwaran <i>et al.</i> 2006
5		<i>A. flavus</i>	Vigneshwaran <i>et al.</i> 2007
6		<i>F. solani</i>	Gadeet <i>et al.</i> 2009
7		<i>F. oxysporum</i>	Khosravi and Shojaosadati. 2009
8		<i>A. alternata</i>	Gajbhiyet <i>et al.</i> , 2009
9		<i>Penicillium brevicompactum</i>	Shaligramet <i>et al.</i> 2009
10		<i>Bipolaris nodulosa</i>	Saha <i>et al.</i> 2010

Bacteria			
11	Gold	<i>Rhodococcus</i> sp.	Ahmad <i>et al.</i> 2003
12	nanoparticle	<i>B. subtilis</i> 168	Fortin and Beveridge, 2000

- 3. Plant Viruses:** Plant viruses, particularly spherical/icosahedral viruses, serve as remarkable examples of naturally occurring nanomaterials or nanoparticles. Among them, the smallest known plant virus is the satellite Tobacco necrosis virus, which measures a mere 18 nm in diameter (Hoglund, 1968). Intriguingly, plant viruses offer a unique avenue for advancing nanoscience and nanotechnology due to their inherent properties. These viruses consist of single or double-stranded RNA/DNA genomes, encapsulated within a protein coat. This protein coat, often resembling a container, serves both structural and functional roles, carrying the nucleic acid cargo from one host to another.

The remarkable abilities of plant viruses to infect host cells, deliver their nucleic acid genomes to specific cellular sites, replicate, package nucleic acids, and exit host cells in a well-organized manner have made them valuable candidates for nanotechnology applications. Plant viruses have been employed as templates for synthesizing diverse types of nanomaterials (refer to Table 2). A comprehensive review detailing the utilization of plant viruses as biotemplates for nanomaterials and their broader applications has been undertaken by Young *et al.* (2008).

Table 2: Nanoparticles Synthesized by Viruses.

Sl. No.	Plant Virus	Application	Reference
1	<i>Cowpea mosaic virus</i> (CMV). an engineered CMV	Iron-platinum nanoparticle (30 nm diameter) synthesis	Shah <i>et al.</i> 2009
2	Cowpea chlorotic mottle virus (CCMV)	Gold nanoparticle synthesis	Slociket <i>et al.</i> 2005
3		As reaction vessel for nanomaterial synthesis	Douglas and Youg. 1998
4	Tobacco mosaic virus (TMV)	Ag and Ni nanoparticle synthesis	Dujardin <i>et al.</i> 2003
5		Synthesis of nanowire of nickel and cobalt	Young <i>et al.</i> 2008
6		Synthesis of ternary alloys of CoPt, CoPt ₃ and FePt nanowires	Tsukamoto <i>et al.</i> , 2007
7	Brome mosaic virus	Gold nanoparticle synthesis	Chen <i>et al.</i> 2005; Dragnea <i>et al.</i> 2003; Sun <i>et al.</i> 2007
8		Iron oxide synthesis	Huang <i>et al.</i> 2007
9	Red clover necrotic mosaic virus	Au, CoFeA- and CdS nanoparticle synthesis	Loo <i>et al.</i> , 2007

VIII. CONCLUSION

In conclusion, nanotechnology presents a new frontier in agricultural research, offering innovative tools and nanodevices that have the potential to replace various cellular processes with enhanced efficiency. While the full extent of nanotechnology's impact on the

agricultural and food industry is yet to be fully realized, significant strides are being made from theoretical understanding to practical application. The integration of smart sensors and intelligent delivery systems into agriculture holds promise for effectively combating crop viruses and pathogens. The development of nanostructured catalysts is expected to enhance the effectiveness of pesticides, enabling precise dosages to be applied as needed. Nanotechnology offers the potential for precise and controlled delivery of agrochemicals, thereby enhancing disease resistance and crop production.

The synergy between nanotechnology and biotechnology has significantly expanded the range of applications for nanomaterials in crop protection and cultivation. As the size of materials and devices continues to decrease, computing power will increase, resulting in stronger materials and more efficient utilization of fungicides for rapid disease control. Nanotechnology's ability to operate at the molecular and atomic scales will undoubtedly shape the future of agriculture. The transformative potential of nanotechnology in revolutionizing agricultural practices is vast, promising to usher in a new era of precision, efficiency, and sustainability in crop management and protection.

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