Exploring Nanoparticles for Effective Management of Plant Pathogens: A Comprehensive Review

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Abstract; Plant pathogens, including bacteria, fungi, and nematodes, continually pose a threat to economically significant crops, causing considerable yield losses. Despite the availability and utilization of diverse chemical treatments, the issue of yield loss still requires attention. Nanotechnology, which exploits the potential of various nanoparticles, offers a dynamic and advanced gateway to plant disease control. Gold, silica, silver, chitosan, cerium, titanium dioxide, alumina-silicate, zinc, gold-silver alloy, and silica-silver are among the nanoparticles employed to combat plant pathogens. These nanoparticles possess antibacterial and antifungal properties, enabling them to modify bacterial cells and impede fungal mycelial growth, making them excellent candidates for deployment against plant pathogens. Moreover, bacteria, fungi, and plants are among the biological sources actively involved in synthesizing nanoparticles. Nanoparticles can also serve as highly effective nanosensors and biomarkers, facilitating faster and more accurate detection of plant diseases. This review paper primarily focuses on nanoparticles' utilization in managing various phytopathogens.

Keywords; Nanoparticle, Plant pathogens, Disease, Detection, Control.

1. Introduction

Different pathogens cause numerous diseases and yield loss to economically important crops. Such pathogens and pests threaten the constant supply of food in the local food chain (MacKenzie & Shane, 1984). Different approaches like cultural, physical, and chemical control have been utilized continuously in the recent past to encounter these issues. Among these methods, chemical control is a prominent method equipped with various chemicals including herbicides, fungicides, insecticides, and weedicides (Hirooka & Ishii, 2013). The chemical method holds some serious issues regarding the biosafety of the environment as it produces toxic residual effects. Other approaches like cultural and physical approaches have facilitated variable control over different pathogens. So, sustainable agriculture demands proper control over different pathogens while utilizing all eco-friendly methods. Keeping an eye on the efficacy and the environmental hazards, science has always looked forward to discovering and exploring new ways. The Discovery and utilization of nanoparticles in the field of plant pathology are one of the new and advanced ways used by science in the current era.

The Greek word 'nanos' gave rise to the word 'nano' which stands for 'dwarf ' equal to the size of 10^9 (D. P. Singh *et al.*, 2016). Any particle that is made up of metal, carbon, metal oxide, or organic material, and attains a size between 1 to 100 nanometers is called a nanoparticle (Refai *et al*., 2015). These particles are of different types like zinc, gold (Au), cadmium (Cd), lead (Pb), silver (Ag), cobalt (Co), copper (Cu), iron (Fe), and (Zn) aluminum (Al) (Ealias & Saravanakumar, 2017). The unique physical, chemical and biological properties of these nanoparticles make them an important weapon to use against numerous plant pathogens. These are variable in shape and size and are amorphous or crystalline (Machado *et al*., 2015). In the field of environmental science, agriculture medicine, and food processing these shape and structure-wise modified nanoparticles have played an important role. So, the agriculture sector has benefited from this latest innovation (Y. W. Chen *et al*., 2016).

Nanoparticles application provides a promising effect over different plant pathogens. Nanoparticles are being applied against plant pathogens in different ways. Their application in the soil is a direct method of using these nanoparticles. Seed treatment is also an option that is done before sowing. Foliar spray of nanoparticles is also being practiced in many cases. Their mechanism of controlling plant pathogens like bacteria and fungi is as same as that of pesticides.

Mahdizadeh *et al*. (2015) proved that the different plant diseases caused by pathogens *Sclerotinia sclerotiorum*, *Macrophomina phaseolina*, *Pythium aphanidermatum,* and *Trichoderma harzianum* were controlled by the application of silver nanoparticles. Similarly, S. Lee *et al*. (2012) examined the effect of zinc oxide on rhizobacteria in rice plants. Pathogenic bacteria including *Azotobacter chrococuum, Bacillus subtilis*, *Pseudomonas syringae*, *Rhizobium tropici*, and *Xanthomonas compestris pv. vesicatoria* has been controlled by the use of nanoparticles. Nanoparticles have also controlled various fungal pathogens such as *Pythium ultimum*, *Magnaporthe grisea*, *Colletotrichum gloeosporioides*, and *Botrytis cinerea* (Hae-Jun, 2006). The cell wall of the targeted pathogen remains intact with these nanoparticles resulting in deformation and eventually, death of the pathogen occurs (Kole *et al*., 2016). The nano-size and the efficacy of these particles can be very useful in the diagnosis of different plant pathogens. Nanoparticles are also being used in the detection of plant pathogens. Their application as a biomarker in the detection of various plant pathogens can be very critical in the timely management of diseases (Sharma *et al*., 2018). The non-targeted organisms like the mineral solubilizing organisms may face the effect of nanoparticles if applied directly to the soil. Therefore, their efficient application methods and the effects of nanoparticles on microbes need to be explored further for the maximum utilization of their potential.

II. Detection of Plant Pathogens:

The timely diagnosis of the different plant pathogens is a key point in controlling the different plant diseases. Timely diagnosis facilitates the antimicrobial chemical application strategies against the targeted pathogens. Nanoparticles as biomarkers are being utilized in the field of plant pathology against microbes like bacteria, fungi, and viruses (Sharma *et al.*, 2018). Methods like visual observation and field identification of the symptoms have been practiced. These old diagnostic methods are costly, slow, and require labor (Kashyap *et al.,* 2017). Molecular approaches like immunological and nucleic acid-based detection are advanced, quick, and precise ways to detect plant pathogens (Kashyap *et al.,* 2017). A precise and cost-effective detection system can be developed with the help of these modified nanoparticles able to link with biological molecules like nucleic acids, peptides, and proteins (P. Wang *et al.,* 2016). Copper-modified gold nanoparticles are involved in detecting the fungal pathogen *Sclerotinia sclerotiorum* infecting oilseed rape (Z. Wang *et al.*, 2010). The fungal pathogen *Tilletia indica* causing Karnal bunt is detected by the use of nanogold particles (S. Singh *et al.*, 2010). CuO (Copper oxide) nanoparticles as biosensors are used for the detection of the fungal pathogen *Aspergillus niger* (Etefagh *et al.*, 2013). Fluorescent silica nanoparticles alongside antibody molecules are employed to uncover the bacterium *Xanthomonas axonopodis pv. vesicatoria* inducing bacterial spot in tomatoes and peppers (Yao *et al*., 2009). *Polymyxa betae*, in Rhizomania disease a vector of *beet necrotic yellow veins virus*, is often detected with the help of quantum dot biosensors (Safarpour *et al*., 2012).

Mycotoxin determination and designing of pathogen nanosensing platforms have been done using the nanocarbon materials like carbon nanowires and nanotubes (Abu-Salah *et al.,* 2015). The nano size and accuracy of the detection of desired material among bulk samples make these systems more attractive to use (García *et al.*, 2010). Zearalenone produced by *Fusarium* sp. can be detected by a precise and fast 'lab-on-chip' strategy (Hervás *et al.,* 2011). The cerium oxide film-based immunosensors are used to detect food-borne mycotoxins (Kaushik *et al.,* 2013). Signal transduction by ion nanogating (STING) sensors with ultra sensitivity is being used to detect the different mycotoxins (Actis *et al.,* 2010). The use of superparamagnetic nanoparticles in enzyme-linked immunosorbent assay (ELISA) is been promising in the detection of aflatoxin-M1 (Radoi *et al.*, 2008). Carbon nanotubes have been used in maize silage samples as an immunosensor to detect the zearalenone (Panini *et al.,* 2010). *Papaya Ring Spot Virus* and *Cucumber Mosaic Virus* were detected by using nanowire biosensors (Ariffin *et al.*, 2014).

The use of nano-biosensors for detection is increasing in the field of agriculture and the food industry. Fast, accurate, and efficient detection of the very minute amount of pathogens like fungi, bacteria, and viruses can be made with the use of these nano-biosensors (Ding *et al.*, 2015). Effective management strategies can be used to control the disease if the pathogen presence is detected at the initial stages. This pre-planned management system can increase crop yield and productivity (Rai & Ingle, 2012). A high concentration of ammonium induces the variation of colors in silver nanoparticles (Dubas & Pimpan, 2008). Copper oxide (CuO) nanoparticles are used for the *Aspergillus niger* detections (Etefagh *et al.*, 2013). Another important application of these nanoparticles is the nano diagnostic kit (Khiyami *et al.*, 2014). The following table.1 illustrates the different nanoparticles being utilized in plant pathology.

Table.1 Different nanoparticles used against Phytopathogens

Nanoparticles	Remarks	References
Nanosilver	Antibacterial & Antifungal	(Velaphi C. Thipe, Marshall Keyster, 2018)
Zinc oxide	Antifungal & Antibacterial	(He *et al.*, 2011), (Fontecha-Umaña *et al.*, 2020)
Silica-Silver composite	Antifungal & Antibacterial	(Hae-Jun, 2006)
Chitosan	Antifungal	(Saharan *et al*., 2013)
TiO_2 nanoparticles	Effective against cowpea diseases	(Owolade *et al*., 2008)
Porous hollow silica nanoparticles	Growth promotor, chemical delivery in plants	(Torney *et al*., 2007)
Aqueous silicate solution	Control powdery & downy mildew	(Kanto *et al*., 2006)
Carbon nanoparticles	Antifungal	(Sarlak *et al*., 2014)

III. Nano-silver:

The biological process of various micro-organisms is interrupted by silver (Pal *et al*., 2007). The bactericidal and inhibitory effect produced by silver is significant (Velaphi C. Thipe, Marshall Keyster, 2018). Different approaches like electron and gamma irradiation, microwave processing laser ablation, biological synthesis, and chemical reduction have been used to produce silver nanoparticles (Iravani et al., 2014). Approaches such as Top-down and bottom-up are the two ways used in different processes of silver nanoparticle production. In the Top-down approach machining, templating, and lithographic techniques are used. Similarly, the self-assembly of the atom into specific structures occurs through the bottom-up approach (Sharma *et al*., 2018). The following table.2 depicts the plant diseases and the pathogens targeted by silver nanoparticles.

Table.2 Silver nanoparticles as an antimicrobial agent

Plant Disease	Microorganisms	
Rice blast disease	*Magnaporthe grisea*	(Elamawi & El-Shafey, 2013)
Collar rot, leaf spot, and root rot	*Alternaria macrospora, A. niger,Rhizoctonia bataticola, Sclerotium rolfsii*	(Khadri *et al*., 2013)
Seed-borne pathogens	*Rhizoctonia solani, Alternaria alternata*	(Kaur *et al*., 2012)
Seed decay, stem blight	*Phomopsis sp.*	(Ri *et al*., 2014)
Pepper Anthracnose	*Colletotrichum* species	(Lamsal *et al*., 2011)
Other plant diseases	*Escherichia coli, Bacillus subtilis, Pseudomonas vulgaris, Pseudomonas aeruginosa*	(Kumar *et al*., 2013)

IV. Carbon nanoparticles:

Carbon is unique in such a way that it forms long chains of atoms by combining in different ways. Carbon is the backbone of the carbon-based nanoparticles. The tube-shaped, horn-shaped, and spherical-shaped arrangements have been observed in the geometrical structure of carbon nanoparticles. The carbon vapors are the building blocks of carbon nanoparticles (Velaphi C. Thipe, Marshall Keyster, 2018). Sarlak *et al*. (2014) stated that the multi-walled carbon nanotubes encapsulated fungicide used against *Alternaria alternata* was more toxic than the non-capsulated one. Arc discharge, laser ablation, and chemical vapor deposition are the ways utilized for the production of carbon nanotubes (Adiloğlu *et al*., 2012).

V. Chitosan nanoparticles:

Chitosan is an antiviral, antifungal, antioxidant, and anti-inflammatory compound. It is also an antimicrobial, bio-adhesion, and adsorption enhancer (Aranaz *et al.*, 2010). Chitosan nanoparticles are very effective against pathogenic bacteria and fungi. Their ability to enhance the growth of plants is also an important feature to notice (Aranaz *et al*., 2010). Spray drying, precipitation, ionic gelation, emulsion cross-linking, sieving, and reverse micellar are among the methods which are used to produce the Chitosan-based agro-nanochemicals (Agarwal *et al*., 2015). In-vitro mycelial growth and spore germination of *Macrophomina phaseolina*, *Rhizoctonia solani*, and *Alternaria alternata* has reduced to a variable degree as a result of chitosan-Cu nanoparticles treatment (Ahuja *et al*., 2012). Chitosan nanoparticles also produce a variable inhibitory effect against the fungal pathogens like *Aspergillus flavus*, *Fusarium oxysporum*, *Fusarium solani*, *Aspergillus niger*, *Sclerotium rolfsii*, *Aspergillus terreus*, and *Alternaria tenuis* (Sahab *et al*., 2015).

VI. Mesoporous silica nanoparticles:

These nanoparticles are used in the targeted delivery of DNA and chemicals into the plants. These nanoparticles are thermally stable (Z. Wang *et al.*, 2010). The development of the independent porous channels in the spherical porous silica nanochannel system has led to the formation of a honeycomb-like structure. This honeycomb-like structure is filled with chemicals that hold it inside. These special structures can reopen resulting in the delivery of chemicals to the cells where they are needed. This technique has been successfully used in maize, Arabidopsis, and tobacco (Kole *et al*., 2016).

VII. Nanosilica–silver composite:

Stress and disease resistance in plants is influenced by silicon (Mao *et al*., 2001). Powdery and downy mildew is also been kept in check by the use of silicate solution (Brecht *et al*., 2004). Disease resistance and the physiological activity of the plants are increased as a result of nanoparticle treatment. Unlike the others, silica effects are variable depending upon the physiological environment. Silver is stable in its ionic form having high antimicrobial activity. The silica-silver combination is found to be effective in controlling many diseases (Hae-Jun, 2006). Pathogens like *Botrytis cinerea, Colletotrichum gloeosporioides, Magnaporthe grisea,* and *Pythium ultimum,* showed 100 % growth suppression when 10ppm solution of silica–silver was applied (Kole *et al*., 2016).

VIII. Less studied Nanoparticles:

Titanium dioxide (TiO_2) is a strong disinfectant and white non-toxic pigment. TiO_2 plays an important role in photosynthesis (Morteza *et al*., 2013). Its pathogen disinfection efficiency is noticeable. So, the scientists are trying to use it in different pathogen-host systems with the help of the dye doping technique. Currently, the TiO_2 photocatalyst technique is being utilized as a plant protection measure in agriculture (Yao *et al*., 2009). Nano-Ce is capable of reducing the disease severity in tomato plants induced by *F. oxysporum* f. sp. *lycopersici* (Adisa & Gardea, 2017). Systemic disease resistance against *Ralstonia solanacearum* in tomatoes can be induced by the preventive application of magnesium oxide (MgO).

IX. Sources of Nanoparticles:

Nanoparticles are synthesized naturally or anthropogenically. Volcanic eruptions, forest fires, simple erosion, photochemical reactions, plants, and animals are the sources through which the nanoparticles are produced. Plants and micro-organisms are the green sources of nanoparticle production. Different bacteria, actinomycetes, fungi, yeasts, and viruses have been used to synthesize gold, silver, selenium, tellurium, platinum, palladium, silica, titania, zirconia, and quantum dots (Li *et al*., 2011).

A.Plant Source:

Possessing a variety of metabolites, plants are the best source of nanoparticles (D. P. Singh *et al.,* 2016). For this purpose, the metal of interest should be present in the growth medium of the plant so that the plant root cells can take it up and pass it through their plasma membrane (Moore, 2006). The nanoparticles cross through the membrane using ion channels during endocytosis. These nanoparticles are accumulated then and distributed throughout the plant. The nature of the metal ion and plant species influences the translocation and uptake of nanoparticles (D. P. Singh et al., 2016). *Brassica juncea* (Indian mustard), *Medicago sativa* (Alfa), and *Helianthus annus* (Sunflower) are the plants that synthesize nanoparticles like silver, nickel, cobalt, zinc, and copper inside them (Bali *et al*., 2006). Silver nanoparticles are formed inside Xerophyte *Bryophyllum* sp. containing anthraquinone emodin when undergoing redial tautomerization. Leaf extracts of the *Magnolia Kobus* and *Diopyros kaki* plants are used in the biological synthesis of gold nanoparticles (D. P. Singh *et al.,* 2016). The leaf extract of *Hibiscus rosa sinensis*, coriander, *Magnolia Kobus*, *Dyopiros Kaki*, *Emblica officinalis* fruit extract, Aloe vera extract, and mushroom extract has led to the development of gold particles having different shapes and morphology (Popescu *et al*., 2010). *Aloe vera*, *Azadirachta indica*, and *Pinus eldarica* are among the plants that synthesize silver nanoparticles (Iravani, 2014).

B.Micro-Organisms:

The cellular structures of bacteria, fungi, and algae are capable of producing the nanoparticles inside them. One example of such organisms capable of producing nanoparticles is diatoms. The basic structural component that takes part in nanoparticle formation is silicon while the precursor that synthesizes nanoparticles is silicic acid. Silicon deposition vesicles, in the vicinity of the cytoplasmic membrane, are the specific vesicles where silicon precursors are transported. Mg-Si oxide replica is formed when diatoms shells are treated with magnesium vapors at high temperatures (D. P. Singh *et al.,* 2016). Bacterial cell precipitates out the gold nanoparticles when incubated with Au^3+ ions (Beveridge & Murray, 1980). *Pseudomonas stuzeri* AG259 produces the silver nanoparticles when incubated in a silver nitrate solution (Beveridge & Murray, 1980). The periplasmic membrane of the bacterium gets accumulated with silver nitrate. *Aeromonas* sp., *Lactobacillus* strains, and *Corneybacterium* are examples of such bacteria that synthesize silver nanoparticles (Iravani, 2014). *Aspergillus furnigatus*, *Verticillium sp*., *Fusarium oxysporum*, *Aspergillus flavus,* and *Phanerochaete chrysoparium* are important fungal organisms synthesizing nanoparticles (D. P. Singh *et al.,* 2016). *Fusarium oxysporum* can synthesize the nanoparticles by utilizing extracellular hydrogenase enzymes. Hydrogenase enzyme is involved in metal reduction because it possesses the redox potential (Shahi & Patra, 2003). Lichen fungi (*Usneea longissima*) can produce bioactive compounds in the laboratory (Shahi & Patra, 2003). *Rhodosporidium diobovatum*, an aquatic yeast, is involved in the intracellular synthesis of lead sulfide (Seshadri *et al*., 2011). Silver nanoparticles are synthesized by the genus *Penicillium* (Sharma *et al*., 2018).

X.Use of Nanoparticles against phytopathogenic Fungi:

The use of nanoparticles to control the different fungal agents is becoming prominent day by day. These nanoparticles are capable of controlling fungal growth. The silver nanoparticles' fungicidal activity for the *Aspergillus brasiliensis*, *Candida glabrata*, *Candida krusei*, *Candida albicans*, and *Candida tropicalis* has been examined. Similarly, silver nanoparticles (AgNPs) possess a high inhibitory effect against fungus due to direct contact with protein and DNA which may lead to the DNA and protein mutation inactivation (G. Chen *et al*., 2000). Hydrogen bond displacement in the base pairs may cause the DNA mutation in fungi (Elechiguerra *et al*., 2005). The cell membrane accumulated with the nanoparticles can alter the functioning of the plasma membrane leading to the death of the cell. The plasma membrane is regulated by the ergosterol compound. Silver nanoparticles disturb the integrity of the fungal membrane leading to the suppression of the normal binding process (Kim *et al*., 2009). Inhibitory effect of nanoparticles of silver on the colonial development of fungi *Magnaporthe grisea* and *Bipolaris* sorokiniana has also been noticed (Jo *et al.,* 2009). *Colletotrichum* species causing pepper anthracnose were tested against the antimicrobial effect of silver nanoparticles (AgNPs) under variable conditions. The mycelial growth of the fungus was significantly inhibited by the use of silver nanoparticles (Lamsal *et al*., 2011). Silver nanoparticles in 15mg concentration prepared from the leaf extract of *Acalypha indica*, possessed excellent antimicrobial action for the tested fungal plant pathogens *Alternaria alternata*, *Sclerotinia sclerotiorum*, *Macrophomina phaseolina*, *Botrytis cinerea*, *Curvularia lunata*, and *Rhizoctonia solani* (Krishnaraj *et al.,* 2012).

The conidial germination of the fungi *Fusarium poae* and *Fusarium graminearum* was significantly controlled by the carbon single-walled nanotubes. The carbon nanotubes with multi-walls also showed an inhibitory effect against these fungal pathogens (X. Wang *et al.,* 2014). X. Wang *et al.* (2014) also concluded that the inhibition effect induced by the nanotubes against these *Fusarium spp.* is due to the induction of plasmolysis and inhibition of water uptake. In the case of fungi causing white-rot i.e., *Trametes versicolor* and *Phlebia tremellosa*, the disruptive oxidative enzyme activation was done by the carbon nanotubes (Berry *et al.,* 2014). The mycelial growth inhibition is achieved by using nanoparticles of nickel *F. oxysporum* f. sp. *lycopersici* and *F. oxysporum* f. sp. *lactucae* (Ruano *et al*., 2016). Nanoparticles of chitosan and copper-chitosan are used to inhibit the spore germination of, *Alternaria alternata*, *Macrophomina phaseolina*, and *Rhizoctonia solani* pathogens (Saharan *et al*., 2013)**.** Magnesium oxide (MgO) nanoparticles significantly reduced conidial germination of *Fusarium oxysporum*, *Alternaria alternata*, *Rhizopus stolonifera*, and *Mucor plumbeus* (Wani & Shah, 2012). The fungicidal activity of Titanium dioxide (TiO_2) nanoparticles has been tested against fungal pathogens *Venturia inaequalis* and *Fusarium solani* (Boxi *et al.,* 2016). Similarly, cerium oxide (CeO_2) nanoparticles are involved in the induction of antioxidant defense system if applied in rice plants (Rico *et al.*, 2013). The defense could also be activated as a result of cerium ion release from the root application of nano cerium oxide. The defense is activated as the released cerium ions form complexes with carboxylic compounds during translocation to the shoots (Zhang *et al.*, 2012). Manganese oxide (MnO_2) nanoparticles show antifungal properties against the pathogens causing wilt diseases in watermelon, eggplant, and tomatoes (Elmer *et al.*, 2018).

Nanoparticles of the zinc oxide (ZnO) are effective biocides against fungal pathogen *Aspergillus niger* (Ruffolo *et al.,* 2010). *Botrytis cinerea* and *Penicillium expansum* has also been controlled by the using nanoparticles of zinc oxide (Sharma *et al*., 2018). Fungal pathogens *Rhizopus stolonifer*, *Fusarium oxysporum*, *Alternaria alternata*, and *Mucor plumbeus* infecting tomatoes were controlled by the application of zinc oxide nanoparticles (Wani & Shah, 2012). The induction of Reactive Oxygen Species (ROS) is a characteristic feature through which zinc oxide (ZnO) inhibits phytopathogens (Ramesh et al., 2017). An induction of reactive oxygen species (ROS) has also been noticed while using selenium (Se) nanoparticles (Soumya *et al.*, 2018). The following figure.1 portrays the signaling pathway induced by Se- ZnO (Selenium Zinc Oxide) nanoparticles in fungus *Macrophomina phaseolina.*

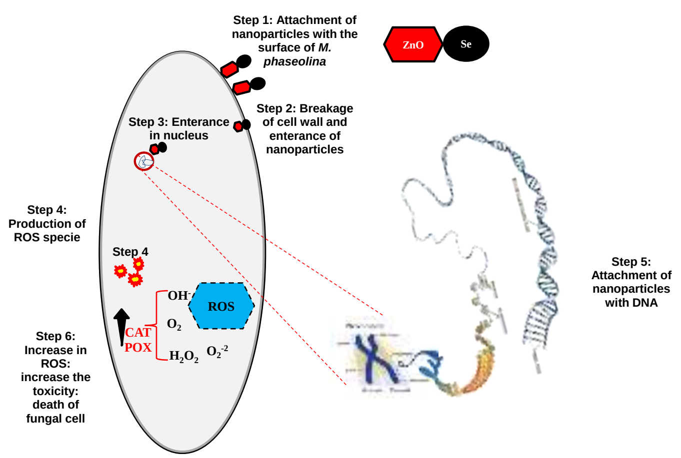

Figure.1 Signaling pathway in fungus (*Macrophomina phaseolina*) induced by Se-ZnO NPs

XI. Use of Nanoparticles against Phytobacteria:

Silver nanoparticles for their antimicrobial effect have been studied against the bacteria *Escherichia coli*, *Pseudomonas aeruginosa,* and *Staphylococcus aureus* (Bryaskova *et al*., 2011). Excellent antimicrobial results are possessed by the silver nanoparticles the against the *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *Escherichia coli* (Lee *et al.*, 2010). The antimicrobial activity of nanoparticles is influenced by factors like metabolism, type of microbial cell, intracellular selective permeability of membranes, concentration, and physiology (Sharma *et al*., 2018). Antimicrobial effects such as denaturation of cell proteins, oxidation of proteins of the targeted pathogen, and alteration of the cell membrane structure are induced by the silver (Dakal *et al*., 2016). Silver nitrate ($AgNO_3$) nanoparticle causes the detachment of the cell wall from the cytoplasm in *Escherichia coli (G. Chen et al., 2000). Xanthomonas perforans* causes the Bacterial spot in tomatoes. The DNA-directed silver nanoparticles were used against the bacterium. The silver nanoparticles held antimicrobial activity against *Xanthomonas perforans* by decreasing the viability of the bacterial cell (Ocsoy *et al.,* 2013). Plant pathogens like *Erwinia cacticida* and *Citrobacter freundii* were effectively controlled by the silver nanoparticles extracted from *Piper nigrum* leaf and stem (Paulkumar *et al.*, 2014). Complete disruption of the cell is caused by copper nanoparticles in *Xanthomonas axonopodis* pv. *punicae* (Mondal & Mani, 2012). In potato plant tissue culture procedures, bacterial contamination was removed by titanium dioxide (TiO_2) (Safavi *et al.*, 2011). Titanium dioxide (TiO_2) holds the antibacterial properties against some soil-inhabiting bacteria (Ge *et al.*, 2011). Graphene oxide, a carbon nanomaterial, was able to kill the cells of *Xanthomonas oryzae* pv. *oryzae* (J. Chen *et al.*, 2013). Magnesium oxide (MgO) nanoparticles have bactericidal properties (Huang et al., 2005). The preventive application of magnesium oxide nanoparticles can lead to systemic resistance against the bacterium *Ralstonia solanacearum* thus, reduce the disease incidence (Cai *et al.*, 2018).

Bacterial pathogens of Plants and food including *Escherichia coli* and *Salmonella enteritidis* are kept in check by nanoparticles of zinc (Jin *et al.*, 2009). *Zinc (Zn) nanoparticles change the cell morphology of the bacteria Sarcina lutea*, *Staaphylococcus aureus*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Bacillus megaterium*, and *Bacillus subtilus* to a lethal level. The growth of *Pseudomonas aeruginosa* was inhibited by the zinc nanoparticles (Jayaseelan *et al.*, 2012). Effective control of some soil-inhabiting bacterial microbes is reached by using zinc nanoparticles as well (Ge *et al.*, 2011). Nanoparticles of zinc oxide exhibit antibacterial action against the different bacteria including *Salmonella enteritidis*, *Pseudomonas aeruginosa*, *Salmonella typhimurium*, and *Pseudomonas fluorescens* (Tayel *et al.*, 2011). These bacteria cause different food-borne diseases in the food industry. Selenium nanoparticles (SeNPs) have also been put to use for their antibacterial activity which is found to be highest against *Klebsiella* sp. (Menon et al., 2020). Alvi et al. (2021) described a promising antibacterial impact exhibited by citrus-synthesized SeNPs. Similarly, X. Huang et al., (2016) disclosed the irreversible impact induced by the SeNPs in bacteria through disruption in bacterial cell membrane and alteration in DNA. Zeebaree et al. (2020) also revealed the cell DNA damage caused by the selenium nanoparticles ultimately leading to the cell cycle arrest. The combined utilization of zinc oxide and selenium nanoparticles is effective against phytobacteria. Like zinc oxide, the rise in Reactive Oxygen Species (ROS) concentration is associated with selenium nanoparticles, too. As a result of this, a decline in viability of cells is observed (Khurana et al., 2019). The following figure.1 illustrates the signaling pathway induced by Se- ZnO (Selenium Zinc Oxide) nanoparticles in the bacteria, *Xanthomonas compestris*.

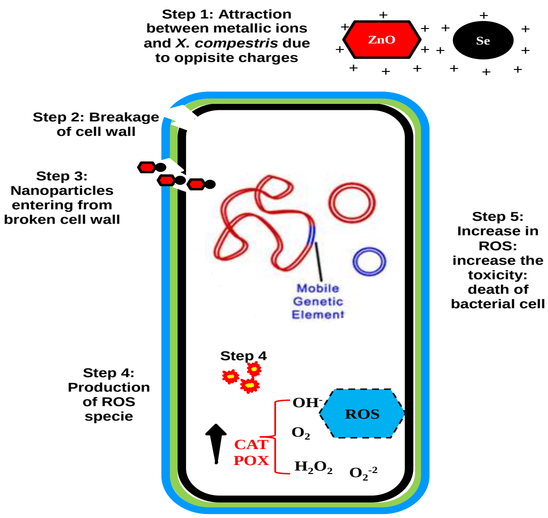

Figure 2. Signaling pathway in *Xanthomonas compestris* induced by Se-ZnO NPs

XII. Use of Nanoparticles against plant-parasitic Nematodes:

Plant-parasitic nematodes are a major threat to agricultural production. Different nanoparticles have shown their nematicidal effect against these nematodes. Several plant-parasitic nematodes have been controlled by using silver nanoparticles (AgNPs) (Roh *et al.*, 2009). The oxidative stress activation mechanism is induced inside the cells of plant-parasitic nematodes by the silver nanoparticles (Lim *et al.*, 2012). *Meloidogyne graminis* juveniles were reduced in number by using high doses of silver nanoparticles in turfgrass. Silver nanoparticles had a nematicidal effect on the root-knot nematode *Meloidogyne incognita* (Abbassy *et al.*, 2017). In eggplant, root galls induced by *Meloidogyne javanica* were significantly reduced by silver nanoparticles (Abdellatif *et al.*, 2016). Silver nanoparticles synthesized from *Azadirachta indica* and *Curcuma longa* were used to control root-knot nematode *Meloidogyne incognita*. Silver nanoparticles of *Curcuma longa* source showed more effective inhibitory results against *Meloidogyne incognita* in comparison to the silver nanoparticles of *Azadirachta indica* source (Kalaiselvi *et al.*, 2017).

Iron nanoparticles hold the nematicidal activity against the plant-parasitic nematode *Meloidogyne incognita* in Okra (Sharma *et al.*, 2017). Gold nanoparticles are effective against *Steinernema feltiae* (Kucharska *et al.*, 2011). In *Caenorhabditis elegans*, silica nanoparticles caused the degeneration of reproductive organs (Pluskota et al., 2009). Similarly, nanoparticles like zinc oxide (ZnO), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3) possess nematicidal activity against the *Caenorhabditis elegans* nematode (H. Wang *et al.*, 2009). Silicon oxide, silver, and titanium oxide nanoparticles were proved to be toxic against second-stage juveniles of root-knot nematode, *Meloidogyne incognita* in lab conditions (Ardakani, 2013). Chitosan-based nanoparticles are used to control pinewood nematode (Liang *et al.*, 2018).

XIII. Conclusion & Future of Nanoparticles in controlling Plant Pathogens:

Plant Pathogens of different types are a serious threat to different economically important crops. The application of nanoparticles in controlling plant pathogens is on a gradual rise. Advancement in this sector can steer to a precise control over the plant pathogens ultimately reducing the yield damages. This can bring about an escalation in prosperity and a cutback in hunger due to production losses among the local food chains. The exploitation of nanoparticles promises a brisk, secure, and accurate control over phytopathogens with an output of high yield and improved quality among crops. Green sources of nanoparticles like plant extracts or production from fungi or bacteria have a low negative impact on humans and other biota. Nanoparticle assembly through such sources can call forth a highly efficient shielded option for integrated disease management. Nanoparticles can play a vital role in not just boosting agricultural production but also guiding us toward sustainability and balance in our environment. Also, nanosensing technology can be of very pivotal significance in the detection of plant diseases. The targeted supply of these nanochemicals can reduce environmental hazards and unwanted contamination. An imminent use of nanoparticles should be encouraged for a positive upswing to achieve biosafety in our environment. As these nanoparticles possess different mechanisms to control pathogens, many areas are yet to be explored and utilized in nanotechnology for better outcomes. Better research efforts are required to explore and utilize the maximum potential of the nanomaterials in controlling plant pathogens

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