CHAPTER

21 Silver-based nanomaterials for plant diseases management: Today and future perspectives

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21.1 Introduction

Crop production declines by plant pests and pathogens infection with global losses estimated at 20%–40% per year (Allinne et al., 2016; Cerda et al., 2017; Cromwell et al., 2014). Traditional control of pests relies heavily on pesticides, such as insecticides, fungicides, and herbicides. Given many benefits, such as high quality, quick action, and efficacy, pesticides have harmful side effects on nontarget species, the revival of the pest population, and resistance (Mohamed and Akladious, 2017; Mohamed et al., 2018). Also, 90% of the pesticides used are projected to be lost during or after application (Ghormade et al., 2011). As a result, there is increased support to produce cost-effective, high-performance pesticides, and ecofriendly compounds that are less environmentally harmful (Aly et al., 2012, 2013, 2017; Abd El-Rahman and Mohamed, 2014; Asran and Mohamed, 2014; Mohamed et al., 2012, 2018; Sofy et al., 2020).

Nanotechnology has contributed to the production of new technologies and agricultural products with tremendous potential for solving the above problems. Nanotechnology in medicine has advanced greatly, although its significance in agricultural applications is comparatively less (Balaure et al., 2017; Sinha et al., 2017). In the sense of hormonal transmission, germination, management of the water and gene transfer targets, tracking nanosensors and control of releases of agricultural products, agriculture nanotechnology use is currently being explored (Hayles et al., 2017). Nanoparticles were engineered by material scientists with specific characteristics such as shape, pore size, and surface properties, so that they can then be used as defensive devices or for accurate and targeted distribution through the adsorption, encapsulation, and/or conjugation of active substances like pesticides

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(Khandelwal et al., 2016). When agricultural nanotechnology develops, there will be a major increase in the ability to provide a new generation of pesticides and other plant disease management tools. Use of nanoparticles for plant defense can take place through two separate mechanisms: (a) nanoparticles which provide protection for crops themselves and (b) nanoparticles as carriers of known pesticides and other active substances, like double-stranded RNA (dsRNA), which may be applied to plants as foliar spray to tissue or drilling/soaking of seeds. As carriers, nanoparticles have many benefits, such as (i) improved shelf-life, (ii) increased solubility of pesticides with low water-solubility, (iii) decreased toxicity, and (iv) improved site-specific target pest uptake (Hayles et al., 2017). Another potential nanocarrier gain involves an improvement in the effectiveness of nanopesticide under environmental pressures (UV and rain) operation and stability and minimizing the number of applications dramatically, thus reducing risk and reducing their costs (Fig. 21.1).

This schematic shows different characterization techniques of nanomaterials and the role of insecticides, fungicides, herbicides, and antibacterial.

Nanoparticles are materials between 10 and 100 nm, which can be built to distinguish between their molecular and bulk counterparts by certain chemical, biological, and physical characteristics (Bakshi et al., 2014). Nanoparticles may be used directly by soaking in plant seeds, foliar spray on leaves or injection in soils to protect against pests and pathogens, including nematodes, bacteria, fungi, or viruses. The studied metals nanoparticles such as platinum, copper, zinc oxide, silver, and titanium dioxide have demonstrated antimicrobial and antiviral properties (Kah and Hofmann, 2014; Kim et al., 2018).

Recently, the widely synthesized form of silver nanoparticles from plants or microorganisms have increased their popularity (Rafique et al., 2017). Well diffusion assay was used to detect the antifungal effect of silver nanoparticles against

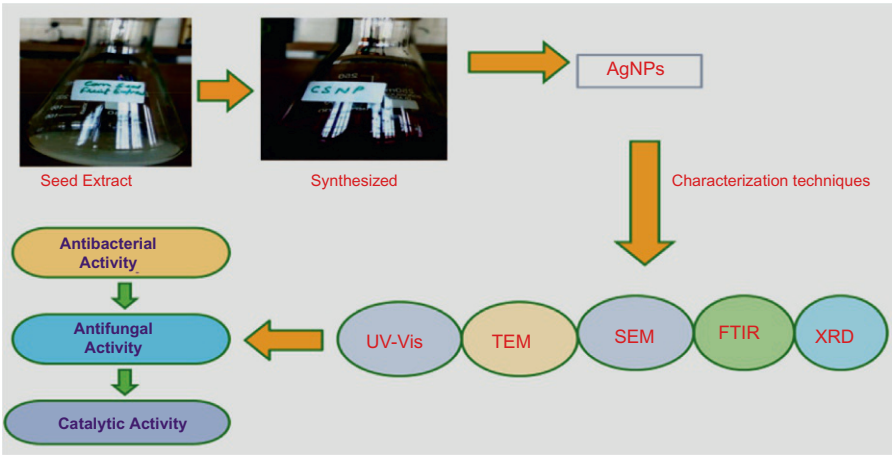

FIG. 21.1

Schematic presentation of synthesized AgNPs, characterization, and their applications.

Macrophomina phaseolina, *Rhizoctonia solani*, *Botrytis cinerea*, and *Curvularia lunata* (Worrall et al., 2018). Also, silver nanoparticles have an antiviral effect against sun-hemp rosette virus (Jain and Kothari, 2014) and bean yellow mosaic virus (Elbeshehy et al., 2015). While plant disease controls against bacterial and fungal pathogens, silver nanoparticles have shown huge potential, they are linked to important obstacles such as growth, toxicity, and soil interaction (Kah and Hofmann, 2014; Mishra and Singh, 2015).

21.1.1 Antimicrobial effect of silver nanoparticles

Because of their antimicrobial capacity, silver nanoparticles are popular and are more harmful to microorganisms than other metallic nanoparticles. Owing to their emergence, these particles are now called antibiotics of the next generation as an alternative to antibiotic therapy. Besides, these particles demonstrated efficacy against different bacteria (both gram-positive and gram-negative) with multidrug resistance (MDR). Despite extensive research and revolutionary research, the exact mechanism of their antimicrobial action is not yet completely understood (Dakal et al., 2016).

The antimicrobial activity of silver nanoparticles is mainly related to the formation of silver ions, and several evidences indicate that Ag^+ silver ions are related to the surface of particles. The high surface area of particles has been shown to release greater Ag^+ concentrations, leading to greater antimicrobial activity, while lower surface area releases depressed levels and gradually reduces antimicrobial activity (Möhler et al., 2018).

21.1.2 Mechanism of antimicrobial effect of silver nanoparticles

AgNPs control the growth of pathogens by several mechanisms. The exact mechanism of AgNPs by which antimicrobial activity is induced is not well known, which is one of the topics covered. AgNPs inhibit growth and prevent different activities of the cellular and molecular systems, and particles can be said to modify the profile of phosphorylation bacterial peptides. Therefore, analyzing this provides an important way of evaluating AgNP toxicity or mechanical behavior (Dakal et al., 2016).

Silver nanoparticles as an antimicrobial mode of action (Patil and Kim, 2017; Tang and Zheng, 2018) such as:

1. Adhesive to the cell membrane surface
2. Alter the structure of cell wall and caused damage to it.
3. Pit formation occurs on the cell surface at the site of disruption in the cell membrane and deposition of AgNPs.
4. Only short exposure to AgNPs allows the precursor envelope to accumulate, conducting proton motive power degeneration.
5. Minimizing the development of cell walls.
6. Inhibit phosphate ion absorption and exchange resulting in membrane leakage for sugar (mannitol), proteins, and amino acid (glutamine and proline).

7. Generation of reactive oxygen species (ROS) and free radical.
8. Inhibit the translation process by binding with ribosomal subunit 30S.
9. The intercalation of DNA bases contributes to block the transcription cycle of DNA.
10. Suppression of DNA replication, blocking of the required electrical potential differences in cytoplasmic membranes and suppression of the respiratory chain.
11. Interact with thiol group of enzymes and protein.
12. Inactivate enzymes which are involved in ATP production.
13. Shift in phosphorylation profile that inhibits the pathway of signal transduction.
14. Prevent the formation of biofilms by halting synthesis of exopolysaccharides

21.1.3 Antibacterial effect of silver nanoparticles

Some NPs influence bacterial growth and stress tolerance, bacterial infection resistance of plants, and processes of contact between plant and associated bacteria (Chen et al., 2016). It has been shown that silver nanoparticles demonstrate effective antibacterial activity against a variety of bacteria that cause diseases (Table 21.1). Nitrification may be the most susceptible microbial phase of the nitrogen cycle, though mild stimulatory impacts can also result from exposure to a limited range of sublethal concentrations of AgNP. Reduced nitrification activity takes place before such nitrogen cycling activities if AgNP levels reach inhibitory levels (Yang et al., 2013).

An increase in silver nanoparticles' (AgNP) antibacterial activity against phytopathogenic bacteria *Ralstonia solanacearum* following stabilizations with certain surfactants such as sodium dodecyl sulfate (SDS), sodium dodecyl benzenesulfonate (SDBS), octylphenol polyethoxylate (TX-100), and polysorbate 80 (Tween 80) as compared to silver ion has been identified by Chen et al. (2016). Owing to the beneficial synergistic effects of the AgNPs and surfactant, Tween 80 is the most preferred stabilizer of AgNPs. All the surfactants, however, almost did not affect Ag^+ antibacterial activity. In vitro, the highest bactericidal activity against *R solanacearum* was seen on Tween 80-stabilized AgNPs. Also, various concentrations of the green synthesized AgNPs (10, 20, 30, and 40 ppm) were exogenously added to *Citrus reticulata* before inoculums of *Xanthomonas axonopodis* pv. *citri* was used to determine canker disease incidence at different intervals of the day. With time, the infection index values were gradually increased in all the treatments applied. AgNPs with a concentration of 30 ppm have been found to be more beneficial for resistance to canker disease (Hussain et al., 2018).

At 20 µg mL^{-1}, the synthesized AgNPs displayed a strong antibacterial activity against the pathogen of rice bacterial leaf blight and bacterial brown stripe while *Xanthomonas oryzae* pv. *oryzae* strain LND0005 had an inhibition zone of 17.3 and 16.0 mm and *Acidvorax oryzae* strain RS-1, respectively. In addition, the

Table 21.1 Silver nanomaterials employed against plant pathogenic bacteria.

Nanomaterials	Bacterial pathogens	References
Ag NPs	*Pantoea agglomerans*, *Ralstonia solanacearum*, *Erwinia amylovora*, and *Pseudomonas lachrymans*	Mohammad and Abd El-Rahman (2015)
	Escherichia coli, *Salmonella typhi*, and *Pseudomonas aeruginosa*	Abalaka et al. (2017)
	Pseudomonas aeruginosa, *Escherichia coli*, and *Bacillus subtilis*	Mohanta et al. (2017)
	Ralstonia solanacearum	Chen et al. (2016)
	Bacillus cereus, *Listeria monocytogenes*, *Staphylococcus aureus*, *Escherichia coli*, and *Salmonella typhimurium*	Patra and Baek (2017)
	Escherichia coli	Ukah et al. (2018)
	Escherichia coli	Shu et al. (2020)
	Pseudomonas syringae	Marpu et al. (2017)
	Xanthomonas axonopodis	Hussain et al. (2018)
	Clavibacter michiganensis	Rivas-Cáceres et al. (2018)
	Acidovorax oryzae strain RS-2	Masum et al. (2019)
	Bacillus sp. and *Enterobacter cloacae*	Singh et al. (2019)
	Acidovorax oryzae strain RS-2	Ali and Abdallah (2020)
	Staphylococcus aureus *Pseudomonas aeruginosa*	Bhuyar et al. (2020)
	Xanthomonas oryzae	Ahmed et al. (2020)
	Candidatus Liberibacter asiaticus	Stephano-Hornedo et al. (2020)
	Leishmania tropica	Javed et al. (2020)
Ag-Chitosan	*Pseudomonas syringae*	Shahryari et al. (2020)

AgNPs synthesized significantly inhibited bacterial growth (Ibrahim et al., 2019). AgNPs reported lowest inhibitory concentrations of 6.25 and 12.5 $\mu g\,mL^{-1}$ against *Xanthomonas axonopodis* pv punicae and *Ralstonia solanacearum* bacterial plant pathogens, respectively. Disk-diffusion in vitro assay showed inhibition zones of 11.4 ± 1 mm and 18.1 ± 1 mm for *R. solanacearum* and *X. axonopodis* pv. *Punicae*, respectively, treated with AgNPs of 50 $\mu g\,mL^{-1}$ (Vanti et al., 2020). Possible function of biosynthesized AgNPs against *Xanthomonas oryzae* pv. *oryzae* was studied. At concentrations of 20, 30, and 50 $\mu g\,mL^{-1}$, we observed good antibacterial activity of biosynthesized AgNPs (size ~12 nm)

against Xoo. Even at the low dose of 5 μg/m, the major inhibitory effect of AgNPs on Xoo's biofilm formation was noted. Additionally, the suppression of disease by biosynthesized AgNPs under greenhouse conditions was authenticated. AgNP foliar spray significantly reduced rice sheath blight symptoms as shown by 9.25% DLA (%Diseased Leaf Area) compared to 33.91% DLA in Xoo inoculated rice plants (Mishra et al., 2020).

AgNPs antimicrobial effect was assessed using paper disk diffusion, colony growth, conidia germination, and in vitro inoculation methods. AgNPs' concentration of 50% inhibition (IC50) against *Setosphaeria turcica* was 170.20 $\mu g\,mL^{-1}$. It also showed a significant antifungal synergistic effect when AgNPs were combined with epoxiconazole in the ratios of 8:2 and 9:1 (Huang et al., 2020).

21.1.4 Mechanism of antibacterial effect of silver nanoparticles

The extensive research in this field has demonstrated that silver nanoparticles can interfere in several cellular and metabolic pathways of cells because of their mechanism of antibacterial action (Arya et al., 2019; Gupta et al., 2018; Aziz et al., 2016) (Fig. 21.2). It can be divided into two groups: (1) the nonoxidative and (2) the oxidative system.

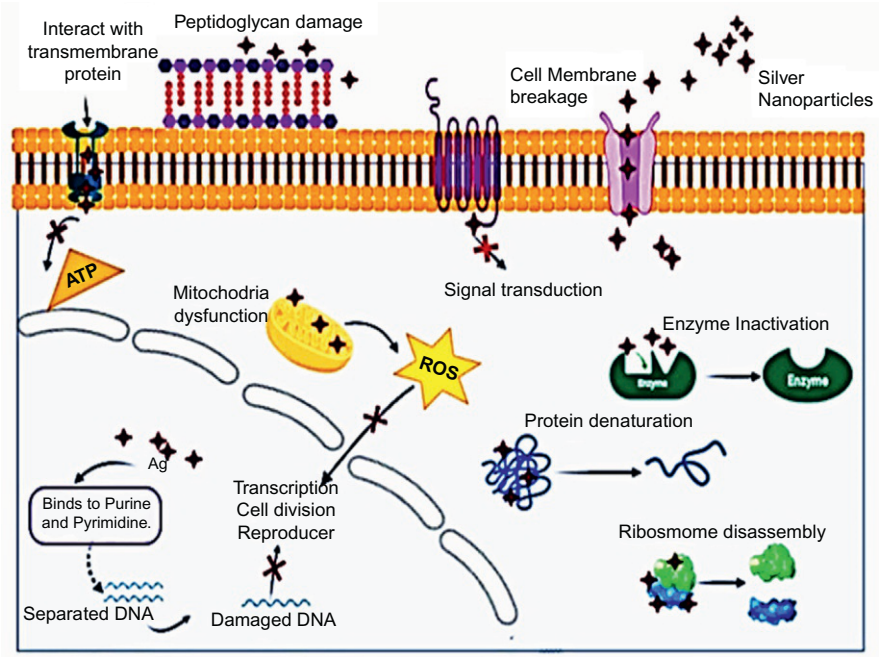

FIG. 21.2

The diagrammatic representation antibacterial mechanisms of silver nanoparticles.

21.2 Nonoxidative mechanism

Anchoring AgNPs to Ag^+ cellular wall formation, modifying membrane structure, destroy of cell walls, penetration in the cell membrane, leakage of the cell portion, and impaired transport activities are the nonoxidative mechanisms for the antibacterial action of AgNP.

21.2.1 Cell wall and cell membrane attachment in bacteria

As AgNPs are contacted with bacterial cells, silver nanoparticles impart the negative charge on the membrane, which makes it easy to attach those AgNPs to the cell wall due to the strong electrostatic interaction. Following attachment, some of these particles are separated to the biologically active Ag^+, and these ions are further connected with the cell wall and released into a cell by Trojan horse mechanism (Singh et al., 2015). These ions further combine with the sugar (β-1,4-conjoined *N*-acetyl glucosamine and *N*-acetyl muramic acid) and amino acid in the layer of peptidoglycan (Agnihotri et al., 2014). This interaction results in morphological changes involving cytoplasmic shrinking and removal of cell membrane (Anitha et al., 2018). This Ag also interacts in the cell wall with sulfur-containing protein, which affects the integrity of the lipid bilayer and causes permeability. This permeability influences the transportation process and impedes the phosphate and potassium ion pump. Excessive permeability eventually leads to cellular leakage in surrounding media causing cell deterioration and inhibition of the cell function, leading to necrosis and cell death (Anitha et al., 2018).

Additionally, this antibacterial activity of nonoxidative process often depends on the type of bacteria, whether gram-positive or gram-negative. The cell wall is composed of 30 nm thick negatively charged peptidoglycan layer in case of gram-positive bacteria, while in gram-negative bacteria the layer is between 3 and 4 nm thick. These changes in the structure and composition make the gram-negative bacteria more sensitive at the same concentration to the antibacterial action of AgNPs rather than gram-positive bacteria (Patil and Kim, 2017).

21.2.2 Damaging the intracellular structure in bacteria

This is more vulnerable to the release of silver ions by penetration following degradation of the bacteria cell wall. The use of surfactant along with these AgNPs has been shown to improve the penetration of AgNPs in the bacterial cells. Such particles interact with protein, lipid, DNA, and other biomolecules after cell membrane penetration (Hsueh et al., 2015; Kumar et al., 2016). AgNPs interact with DNA, leading to denaturation and damage to the DNA. These particles cause in the loss of DNA replicability because of a transition in relaxed to condensed state (Khalandi et al., 2017). The Ag^+ produced by AgNPs interacts separately with the purine and pyrimidine base and destabilizes the double-helical and β-sheet DNA structure, resulting in inhibition of gene transcription, so that, this contributes to cell

division inhibition and their reproduction (Hsueh et al., 2015; Kumar et al., 2016). In addition, the AgNPs interact with the ribosomal subunit and help desaturate the translation cycle. These ions also inhibit proteins that take part in the generation of ATP transmembrane by reacting with the thiol group, interacting with the protein functional group and inhibiting its deactivation (Arya et al., 2019). Furthermore, these ions are interfering with synthesized protein by altering or blocking its active binding site and impairing its overall efficiency, resulting in a general functional defect in the microorganism (Arya et al., 2019).

21.3 Oxidative-stress mechanism

Oxidative stress is a disorder caused by the difference in the reactive oxygen species level (ROS) and free radical so that increases the free radicals can cause toxic effects (Quinteros et al., 2016). Increased oxidative cell stress of microbes is the responsibility of AgNPs, which is consistent with particulate antibacterial capacity. The increased Ag^+ concentration produced via AgNPs surface area after bacterial interaction is shown by the electron spin resonance spectroscopy studies, which are expected to cause higher ROS like hydrogen peroxide (H_2O_2), hydroxyl radical, superoxide anion (O_2^-), hydroxyl radical (OH), hypochlorous acid (HOCl), singlet oxygen, and free radical production (El-Beltagi and Mohamed, 2013). The large amounts of ROS and free radical caused breakage of the mitochondrial membrane and single-strand DNA, and the death of cells. As AgNPs interacts with bacterial cell, the Ag^+ released interacts with the thiol group of reduced glutathione and other enzymes that perturb the scavenging mechanisms. GSH is converted into oxidized forms of GSSH glutathione disulfide (Tang and Zheng, 2018). This Ag^+ also binds to the bacterial cell membrane and induces instability in the respiratory electron transporter chain and inhibits enzymes in the respiratory chain (Korshed et al., 2016; Gupta et al., 2018; Pareek et al., 2018; Prasad et al., 2017).

21.3.1 Antifungal effect of silver nanoparticles

Some researchers documented the antifungal activity of AgNPs on certain pathogenic fungi (Table 21.2). The mycelial growth and germination of incubated spores is observed to significant decrease with the use of AgNPs (Ahmed, 2017).

Many AgNPs have antifungal properties for other fungi, such as *Fusarium* species and other phytopathogenic fungi. Different studies have shown that antifungal activity against fungal pathogens can be caused by the fungal pathogens' suppression of enzymes and toxins (Dean et al., 2012). *Colletotrichum gloeosporioides*, which causes fruit anthracnose, has been used to test the antifungal activity of silver NPs. The mycelial growth of *Colletotrichum gloeosporioides* decreased dramatically in dose-dependent ways (Aguilar-Méndez et al., 2011).

The synthesized Ag NPs demonstrated excellent fungicidal activity against *Cladosporium fulvum*, which is the main cause of a serious plant disease called

Table 21.2 Silver nanomaterials used as fungicides against plant pathogenic fungi.

Nanomaterials	Fungal pathogens	References
Ag NPs	*Penicillium digitatum*, *Alternaria citri*, and *Alternaria alternata*	Abdelmalek and Salaheldin (2016)
	Candida albicans	Ali and Abdallah (2020)
	Phomopsis vexans	Mahawar and Prasanna (2018)
	Alternaria alternata	Abbas et al. (2019)
	Alternaria alternata, *Penicillium digitatum*, and *Alternaria citri*	Abdelmalek and Salaheldin (2016)
	Aspergillus flvus and *Fusarium solani*	Villamizar-Gallardo et al. (2016)
	Macrophomina phaseolina	Mahdizadeh et al. (2015)
	Candida spp., *Aspergillus* spp., and *Fusarium* spp	Xue et al. (2016)
	Macrophomina phaseolina, *Alternaria Alternata*, and *Fusarium oxysporum*	Bahrami-Teimoori et al. (2017)
	Sclerotinia homoeocarpa	Li et al. (2017)
	Aspergillus niger, *Aspergillus flavus*, and *Aspergillus fumigates*	Menon et al. (2017)
	Alternaria solan	Abdel-Hafez et al. (2016)
	Fusarium oxysporum	Maroufpoor et al. (2019)
	Rhizoctonia solani, *Fusarium oxysporum*, and *Curvularia* sp.	Balakumaran et al. (2016)
	Alternaria solani	Kumari et al. (2017)
	Alternaria alternate, *Rhizoctonia solani*, *Botrytis cinereal*, and *Fusarium oxysporum*	Almadiy and Nenaah (2018)
	Fusarium moniliforme	Kalia et al. (2020)
	Setosphaeria turcica	Huang et al. (2020)
	Botrytis cinerea	Faghihi et al. (2020)
Starch stabilized AgNPs	Candida species	Prasher et al. (2018)
Ag core-DHPAC shell nanocluster	*Phytophthora capsici*, *Phytophthora nicotianae*, and *Phytophthora colocasiae*	Ho et al. (2015)
	Fusarium graminearum	Ibrahim et al. (2020)
AgNPs/chitosan	*Corynespora cassiicola*	Nhien et al. (2018)
AgNPs-Ce	*Alternaria alternata*	Mahawar et al. (2020)
Essential oils (EOs) of thyme (*Thymus daenensis* L.) and dill (*Anethum graveolens* L.) with AgNPs	*Colletotrichum nymphaeae*	Weisany et al. (2019)

tomato leaf mold. The increase in inhibition zone reduction activity is observed with the increase of Ag NPs concentration. Such promising results can be exploited further by using the AgNPs against different pathogenic fungi to assess their range of fungicidal activity (Elgorban et al., 2017). Kaman and Dutta (2017) studied the effect of silver nanoparticles at various concentrations (10, 30, 50, and 100 ppm) as an antifungal against four soil-borne plant pathogens. The results found that the growth of pathogenic mycelia at 100 ppm of the silver nanoparticles. Also, two concentrations of AgNPs (50 and 100 $\mu g\,mL^{-1}$) were used in in vitro experiments to research their role as an antifungal action against plant pathogens *Xanthomonas axonopodis* pv. *malvacearum* and *Xanthomonas campestri*s pv. *campestris*. The results showed zone of inhibition 11.0 ± 1.0 and 12.3 ± 0.5 mm for *X. axonopodis* pv. *malvacearum* and 9.7 ± 0.6 and 15.33 ± 1.0 mm for *X. campestris* pv. campestris (Vanti et al., 2019). The silver nanoparticles' antimicrobial activity was tested against *Fusarium oxysporum* and *Colletotrichum gloeosporioides*. Total inhibition on *F. oxysporum* was detected at a silver nanoparticles concentration of 75 ppm. No growth at 100 ppm silver nanoparticles was observed in vitro for *C. gloeosporioids* (Singh et al., 2019). The inhibitory activity of silver nanoparticles (AgNP) at concentrations of 10, 20, 50, and 100 ppm was assessed against two phytopathogens: *Bipolaris sorokiniana* and *Alternaria brassicicola*. The results showed that 20 ppm of AgNP caused a greater reduction in germinating spores of *B. sorokiniana* and *A. brassicicola*. Alternatively, 100 ppm of AgNP may be preferred to restrict the mycelial development of these pathogens (Kriti et al., 2020). Talie et al. (2020) found that AgNPs at highest concentrations (20 $mg\,mL^{-1}$) caused the highest inhibition in spore germination and maximum zone of inhibition against *Penicillium chrysogenum* followed by *Aspergillus niger* and *Alternaria alternata*, respectively.

In addition, AgNPs synthesized by the leaf extract from *Ligustrum lucidum* exhibited prominent antifungal activity against *Setosphaeria* (Huang et al., 2020). Moreover, after exposure to AgNPs both in vivo and in vitro, effective inhibition of *Fusarium oxysporum*, the causal agent of tomato wilting, was achieved. In vitro studies showed repressed mycelial fungal growth with an inhibition of 79%–98% compared to control (Anjum and Ashraf, 2020). Biosynthesized AgNPs showing strong inhibition of mycelium formation, spore germination, germ tube length, and mycotoxin production of wheat *Fusarium* head blight pathogen *Fusarium graminearum* (Ibrahim et al., 2020).

21.4 Mechanism of antifungal effect of silver nanoparticles

Ion efflux dysfunction may result in a rapid accumulation of silver ions by reacting to the molecules and prevent cellular activity at lower levels, for example, metabolism and respiration. Silver ions can also generate reactive oxygen species that are dangerous to cells by interacting with oxygen and cause nucleic acid, lipid, and protein damage (Hwang et al., 2008).

Some hypotheses suggest the Ag NPs mechanism is antifungal (Fig. 21.3).

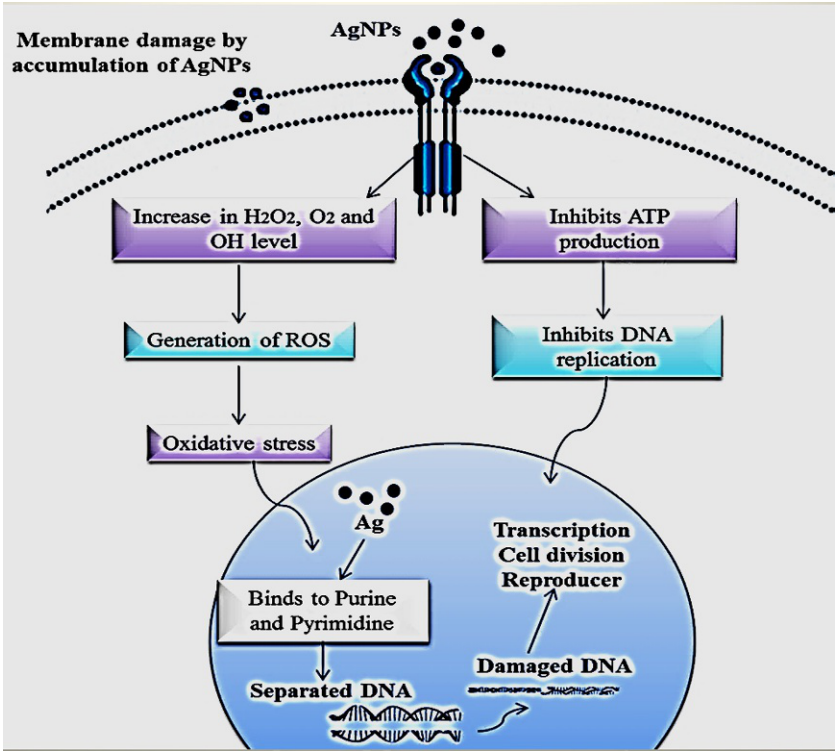

FIG. 21.3

The diagrammatic representation antifungal mechanism of silver nanoparticles.

1. The increase in Ag NPs could impregnate and adhere to fungal hyphae, thus inactivating pathogenic plant fungi (Lemire et al., 2013).
2. Ag NPs linked to the cell wall trigger cell lysis, causing structural damage and destroying the cell 's proper activity and contributing to the end of cell life of microbes (Rai et al., 2009).
3. After Ag application, the DNA will not be able to replicate and ribosomal protein expression will be disabled. In addition, certain other cellular proteins and enzymes are required to produce ATP. Ag^{+} is thought to primarily affect the role of membranous enzymes, such as those in the respiratory chain (Kim et al., 2012).
4. Cells die by using Ag NPs because of their effect on ribosome causing protein inhibition (Prabhu and Poulose, 2012).
5. In another study by Kumar et al. (2016), Ag NPs enter via phagosome process into the fungal cell membrane and nucleus, then bind to chromosomes, and cause chromosomal damage.

21.4.1 Effect of silver nanoparticles on plant-parasitic nematodes

More than 4000 plant pathogenic nematodes are known to cause significant harm to nearly all plants (Nicol et al., 2011). Annually, the estimated crop loss due to nematodes reaches about 14.5% worldwide (Abd-Elgawad and Askary, 2015). The phylum Nematoda plant-parasitic nematodes were divided into two orders: Tylenchida and Dorylaimida. Both the Dorylaimida genera (Xiphinema, Longidorus, Paralongidorus, Trichodorus, and Paratrichodorus) are migratory ectoparasites. They are known to target trees and herbaceous crops by transmitting phytopathogenic nepo- and tobra-viruses that seriously harm the plants (Abd-Elgawad and Askary, 2015). All plant parts are infected by nematode species like roots, bulbs, rhizomes, stems, leaves, buds, flowers, and seeds. The root-knot nematode (*Meloidogyne* spp.) is especially a severe pathogen for a lot of crops (Abd-Elgawad, 2014). The wide use of nematicides can lead to problems for the environment and health, and nematodes resistance. Therefore, it is important to apply effective, low-cost, and safe alternative control strategies to producers, consumers, and the environment (Abd-Elgawad, 2014).

In laboratory and field experiments, the nematicide effect of silver nanoparticles (AgNPs) was evaluated. They concluded that high doses of application of AgNPs (average 90.4 mg/m^2) were found to be effective in decreasing the number of *Meloidogyne graminis* juveniles in turfgrass (Cromwell et al., 2014). In addition, Nassar (2016) assessed the effectiveness of Ag-nano formulations of *Urtica urens* extracts against root-knot nematodes (*Meloidogyne incognita*), and he found that the petroleum ether extract effect and its Ag nanoparticles provide a sufficient and environmentally safe way to minimize *Meloidogyne incognita*. Moreover, Abdellatif et al. (2016) confirmed the substantial reduction of root galls due to root-knot nematode (*Meloidogyne javanica*) infection after application of AgNPs. Moreover, Taha and Abo-Shady (2016) reported that treatment with AgNP concentration (1500 ppm) caused a reduction in *Meloidogyne incognita* nematode populations associated with tomatoes. Results revealed nematicidal activity of leaf extracts of *Conyza dioscoridis* that were prepared as silver nanoparticles (AgNPs) had great nematicidal activity against the 2nd stage juvenile (J2) and eggs of *Meloidogyne incognita*.

Also, Nour El-Deen and El-Deeb (2018) observed that the use of AgNP in a tomato field against the root-knot nematode was very successful when compared with the application of control or silver nitrate. A series of laboratory tests (water and sand screening) and glasshouse experiments (using a soilless method, autoclaved soil, and naturally infested soil) were conducted to investigate AgNP nematicide effects on *Meloidogyne gramnicola*. Results from laboratory assays showed 0.1 $\mu g\,mL^{-1}$ in the water screening test as the minimum concentration for 100% irreversible nematode mortality after 12 h. However, after 24 h of incubation, tests from the sand screening test showed 100% nematocidal effect of AgNP at 2 $\mu g\,mL^{-1}$. In glasshouse assays in soilless rice cultivation method, 1 $\mu g\,mL^{-1}$ AgNP concentration applied directly to the trays achieved substantial suppression of the formation of root gall.

In addition, Barbosa et al. (2019) found that AgNP (*Duddingtonia flagrans*) demonstrated nematicide effectiveness, being the only treatment able to penetrate the larvae cuticles and cause their subsequent death. Hamed et al. (2019) found that in vitro assay against the nematode of the root-knot *Meloidogyne javanica* showed that AgNPs significantly reduced eggs hatching with *M. javanica* applied at various concentrations (3%, 6%, 12%, 25%, and 50%, v/v). The highest reduction rate (94.66%) was caused by 50% of AgNPs. Also, the AgNPs and $AgNO_3$ substantially improved larval percentages mortality of second-stage juvenile (J2). AgNPs or $AgNO_3$ at 2, 4 mL L^{-1}, 24 h completely inhibited J2 growth compared to 23% inhibition with aqueous cyanobacterial extract. Nazir et al. (2019) showed that silver nanoparticles' (AgNPs) nematicidal behavior was investigated against nematode with the most damaging root-knot (*Meloidogyne incognita*). Maximum juvenile mortality was reported at a concentration of 100 mg mL^{-1}, followed by AgNP at 75 mg mL^{-1}. AgNP at 25 mg mL^{-1} showed minimum mortality, the rise in concentration, a related increase in juvenile mortality revealed a clear relationship between mortality and concentration of nanoparticles. Also, the effective dose to kill nematodes in field soil assays was 3 µg mL^{-1}, which is less than the 150 µg mL^{-1} value (Baronia et al., 2020).

21.4.2 Mechanism of nematocidal effect of silver nanoparticles

AgNP has demonstrated high potential as a strong nematicide, whose impact is associated with oxidative stress induction in PPN cells and the disruption of membrane permeability and ATP synthesis by the cellular mechanism (Lim et al., 2012). The nematicide function of AgNPs for microorganisms may be associated with development silver surface free radicals, which lead to increased oxidative stress and damage to the membrane (Khalil and Badawy, 2012).

21.4.3 Effect of silver nanoparticles on antiviral

Apart from being an antibacterial and antifungal agent, AgNPs have also been recognized as antiviral agents. Plant viruses are occurred in nature and cause serious diseases in different plants. They were causing significant crop quality and yield losses. Virus diseases account for 47% of this decline, out of 15% of world food production is lost due to plant diseases (Boualem et al., 2016; Sofy et al., 2020).

Postinfection application with AgNPs resulted in a significant decrease in virus concentration, infection percentage, and severity of the disease. Accordingly, the AgNPs were confirmed to be effective against a prototype arenavirus when administered early after initial exposure to the virus (Speshock et al., 2010). Also, Jain and Kothari (2014) found that spraying of 50 ppm aqueous solution silver nanoparticles on cluster bean leaves inoculated with sunhemp rosette virus (SHRV) showed complete disease severity reduction, suggesting that silver nanoparticles are antiviral-effective. In addition, treatment with AgNPs led to a decrease in the percentage of BYMV infection and disease frequency (Elbeshehy et al., 2015). El-Dougdoug et al. (2018)

studied the efficiency of silver nanoparticles (AgNPs) as an antiviral reagent inducing systemically acquired resistance (SAR) to tomato mosaic virus (ToMV) and potato virus Y (PVY) and suppressing tomato plant infection. The findings showed that the severity of the disease and the relative concentration of both viruses were significantly reduced by treating AgNPs at 50 ppm vs the other treatments. Examination of the clarified sap of both viruses by transmission electron microscope (TEM) showed morphological evidence that AgNPs bind to coat particles of the protein virus.

21.4.4 Mechanism of antifungal effect of silver nanoparticles

Ag inactivates viruses in various ways by denaturing enzymes by reactions with sulfhydryl, amino, carboxyl, phosphate and imidazole groups (Rai et al., 2009). AgNPs may inhibit the replication of viral nucleic acid and its antiviral activity may be due to several factors such as: particle size, distribution of ligand/receptor molecules that interact (Papp et al., 2010). The silver nanoparticles can communicate with microbial cells directly. Silver ions can disrupt the transmembrane electron transfer, oxidize cell components and perpetration in the cell chain and make the cells susceptible to reactive oxygen species (ROS), or dissolve heavy metal ions causing harm in particular, the enzymes in the respiratory chain and the permeability of phosphates and protons (Rajeshkumar and Malarkodi, 2014). In addition, more damage to bacterial cells can be caused by cell permeation, where they interact with proteins, DNA, and other cell-containing constituents of sulfur and phosphorus (Nayak et al., 2015). AgNPs have also shown to resist viral membrane fusion, thereby

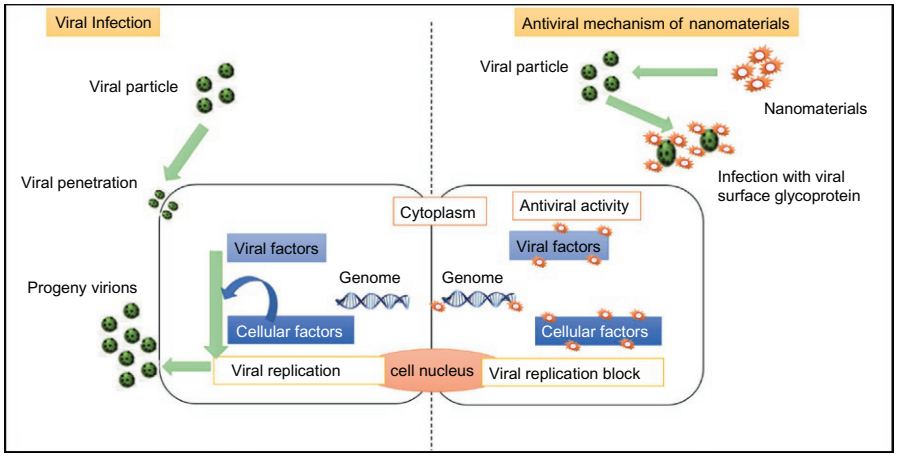

FIG. 21.4

Schematic model of viruses that infect live cells and the metal nanomaterial antiviral mechanism.

preventing the virus from entering the host cell (Mohamed and Abd-Elsalam, 2018) (Fig. 21.4).

21.4.5 Postharvest diseases

It is estimated that about 20%–25% of the fruits and vegetables harvested are contaminated by pathogens even in developing countries during postharvest handling. Postharvest losses are often more severe in developing countries due to insufficient storage and transport facilities (Yahaya and Mardiyya, 2019). The Food and Agriculture Organization of the United Nations announced the world's food supply loss of 35% after losses in the production system have accumulated because of the disease pathogen (Gastavsson et al., 2011).

Several pathogenic agents such as fungi and bacteria are responsible for causing plant diseases. It is nevertheless well known that the big postharvest losses are caused by fungi such as *Alternaria*, *Aspergillus*, *Botrytis*, *Colletotrichum*, *Diplodia*, *Monilinia*, *Penicillium*, *Phomopsis*, *Rhizopus*, *Mucor*, and *Sclerotinia* and bacteria such as *Erwinia* and *Pseudomonas* (Sheikh, 2017). The highest risk of mycotoxin contamination arises when contaminated plants are used for food or animal feed production (Greeff-Laubscher et al., 2020). At present, controlling degradation of fruit and vegetables after harvest is currently achieved by applying chemical fungicides such as imazalil, thiabendazole, pyrimethanil, and fludioxonil to citrus or boscalid and iprodione to grapes (Palou, 2018). When used as sanitary agents, chloride-based chemicals can formulate organic chlorinated substances, including chloramines, dichloramines, and trichloromethane, known to be respiratory irritants (Fallanaj et al., 2013). On the other hand, the widespread use of chemical fungicides pre- and postharvest has caused resistant strains of pathogens that break down the efficacy of the fungicide (Hao et al., 2011). Although these techniques are expensive and time-consuming, the technological existence of fungicides after a period of time is essential (Vitale et al., 2016). In addition, customers are concerned about the use of chemical fungicides, as their active ingredients and coformulants are linked to health problems and environmental pollution (Nicolopoulou-Stamati et al., 2016). Nanomaterial therapies have recently studied and shown promising results to minimize the use of synthetic fungicides in fruit and vegetable rot after harvest (Ruffo et al., 2019).

In the section of postharvest fruit and vegetable industry, nanotechnology approach is helpful for postharvest disease control, the launch of innovation for packaging films, to prevent the impact of gases and unsafe rays, to improve the appearance of packaging, and help with multiple chips (nanobiosensors) to mark fresh products (Ruffo et al., 2019).

The antifungal effects of nanocomposites SiO_2/Ag_2S (300 nm) were first recorded in *Aspergillus niger*, the most common postharvest fungus causing many diseases of the fresh fruit like apples and oranges (Plascencia-Jatomea et al., 2014). The results indicate that the sporulation and growth of fungi are decreased by SiO_2/Ag_2S nanocomposites. This effect was observed because Ag_2S nanophases and the synergistic effect of Ag_2S and SiO_2 surfaces in support of fungal adsorption were present (Fateixa et al., 2009). It

has been suggested that silver species associate in the plasma membranes of susceptible pathogens with the sulfydryl groups of respiratory enzymes, causing changes in the membrane permeability (Ruffo et al., 2019). The binding of Ag^{+} to microbial genetic material was another theory to clarify this mechanism (Han et al., 2011).

AgNPs (38 nm), CuNPs (20 nm), and Ag/CuNP were examined in vitro studies at various levels (0, 1, 5, 10, and 15 mg L^{-1}) against *Alternaria alternata* and *Botrytis cinerea*. The optimal level is 15 mg L^{-1} for inhibiting both pathogens. The nanoparticles weakened the hyphae and conidia of *A. alternata* using a scanning electron microscope. In *B. cinerea*, fungal hyphae were found to have weakened their surface, leading to the release of inner cell materials with shrinking pathogen hyphae. Also, total culture filtrate protein and total cell wall protein and *N*-acetyl glucoseamine decreased, while total culture filtrate and cell wall lipids increased after treatments with silver nanoparticles (Ouda, 2014).

In another in vitro study, silver nanoparticles (50 nm) were prepared and mixed with the fungicide tolclofosmethyl at various concentrations (25–100 mg L^{-1}). The mixture worked better against *B. cinerea* than individual compounds (Derbalah et al., 2011).

The composite of chitosan–silver NPs (diameter 495–616 nm) was prepared, and the silver NPs were distributed in 10–15 nm size composite. The composite exhibited greater antifungal effect against *Colletotrichum gloeosporioides* conidial germination. A complete spore germination inhibition was obtained when a composite of chitosan-silver NPs was applied at 100 μg mL^{-1}. Furthermore, in vivo studies showed a decrease in anthracnose disease of about 45.7% and 71.3% by composite chitosan-silver nanoparticles of 0.5% and 1%, respectively (Chowdappa et al., 2014).

The copper oxychloride-conjugated silver NPs were tested by Raghavendra et al. (2019) for their action against the mango anthracnose causative agent (*C. gloeosporioides*). The nanomaterials with an average particle size of 21–25 nm displayed the pathogen maximum growth inhibition (~187%) compared with copper oxychloride.

Ag NPs caused the release of Ag ions at the desired rate and position to naturally affect the microbe cell. The presence of ligands in the bacteria's vicinity is considered a problem using Ag ions directly as a toxic to bacteria, as it can bind to Ag ions, blocking them from reaching their target (Xiu et al., 2012). The AgNPs, therefore, serve as a highly efficient source for Ag ions to the cytoplasm and membrane of bacterial cells, where natural ligands are less associated with exposure or reduction. Consequently, several efforts were made to modify the NP surfaces. AgNPs modified with glucose, lactose, oligonucleotides, and these ligands' combinations have been tested for their cytotoxicity (Sur et al., 2010). Silver nanoparticles demonstrated excellent bactericidal properties against several microorganisms (Siddiqi and Husen, 2016; Wei et al., 2015). Owing to its inherent characteristic, it displayed an antimicrobial characteristic and a significant role even in solid state (Siddiqi et al., 2018). Several studies revealed the inhibitory nature of Ag NPs particles linked to sterilization (Kim et al., 2011). Inhibitory effect of silver nanoparticles was recorded

on plant postharvested disease pathogens, *Botrytis cinereal* (Salem et al., 2019), *Penicillium verrucosum* (Mukherjee et al., 2016), *Fusarium oxysporum* (Abkhoo and Panjehkeh, 2016; Bahrami-Teimoori et al., 2017), *Alternaria alternata* (Bahrami-Teimoori et al., 2017), *Colletotrichum musae* (Jagana et al., 2017), *Sclerotinia sclerotiorum* (Guilger-Casagrande et al., 2019), *Penicillium digitatum* and *Alternaria citri* (Abdelmalek and Salaheldin, 2016), and *Aspergillus niger* (Al-Zubaidi et al., 2019).

Due to its nanometric size, which facilitates interaction with microbial cells, silver nanoparticles have a biocide effect, small AgNPs interact with cell membranes, modify the lipid bilayer, increase membrane permeability, and finally, cause cell death (Li et al., 2013). Ag NPs have been found to be detrimental to DNA (Han et al., 2011). It can form complexes with DNA nitrogen bases, thus condensing and reducing the process of replication and reacting with proteins, thus affecting the respiratory and cell division (Ruffo et al., 2019).

21.4.6 Pathogens detection and diagnosis

A global food shortage will continue in the next 40 years, as steady growth in the human population is anticipated. To meet the needs, a 70% increase in food production is required by 2050. Unsafe food is a concern to human health and the economies of countries, which affects people primarily. There are believed to be 600 million cases of food-borne diseases and 420,000 deaths worldwide annually (Zorraquin-Pena et al., 2020).

In-plant disease diagnosis, various direct and indirect methods are used, which are laboratory-based techniques such as nucleic acid detection based on polymerase chain reaction (PCR), in situ fluorescence hybridization, enzyme-linked immunosorbent assay (ELISA), immunofluorescence, flow cytometry, thermography, fluorescence imaging, hyperspectral techniques, and gas chromatography (Fang and Ramasamy, 2015). The key downside of these approaches is long analytical time ranging from several hours to days, usually with different phases of pretreatment (Omanović-Mikličanina and Maksimović, 2016).

The lack of traditional methods for solving new food safety challenges leads to the development of new techniques with miniaturized and quick analytical power and low detection limits. Key solutions in developing new nanotechnology-based devices integrated with analytical tools (Omanović-Mikličanina and Maksimović, 2016). Nanoparticles can be synthesized using various types of materials for electronics and sensing applications because they exhibit fascinating electronic and optical properties (Sun et al., 2014, 2017). Recently, various types of phytopathogens such as bacteria, viruses, and fungi were detected through amperometric biosensors based on nanoparticles (Chartuprayoon et al., 2010). The use of nanosensors as a detector of pathogens, toxins, pollutants, and food freshness emerges as a promising method in agriculture and food protection (Joyner and Kumar, 2015). It also uses physiological signals in detection and

converts them into standardized, often electrical signals which can be quantified from analog to digital signals.

Due to the low cost, simplicity, and convenience of these methods, metal nanoparticules colorimetric assays have received considerable attention (Laksanasopin et al., 2015). Metal nanoparticles have been used as marker tags in several biosensor formats to replace labeling enzymes or other chromophores such as gold (AuNPs) and silver (AgNPs) nanoparticles, which have been tremendously used to detect analytes. AgNP is a broad-spectrum antimicrobial agent, which can affect plant pathogens and bacteria (Wu et al., 2011). These results may be due to its mode of action because it demonstrated strong adhesion on the surface of bacterial and fungal cells (Seong and Lee, 2017). For its simplicity and practicality, colorimetric detection has been widely applied (Song et al., 2011).

For the detection of multiplex mycotoxins with ultrahigh sensitivity, high throughput, and simplicity, a novel surface-plasmon-coupled chemiluminescent immunosensor was developed. The immunosensor was built by immobilizing carboxyl-modified silver nanoparticles (AgNPs) and bovine serum albumin combined antigens sequentially on the modified amino-grouped glass chip. The optical properties of AgNPs could amplify the chemiluminescence (CL) generated on the chip by the resonance phenomenon of surface plasmons (Jiang et al., 2020).

The SERS-sensor holds promise for the rapid quantification of Ochratoxin-A (OTA) and aflatoxin-B1 (AFT-B1) in cocoa beans at pg/mL level to enable safety assurance in the cocoa bean industry. AgNP@pH-11 was selected to manufacture SERS-sensor with the highest SERS-EF (1.45/108) and coupled with two chemometric algorithms to predict OTA and AFT-B1 in standard prepared solutions (SS) and spiked-cocoa-beans samples (SCBS) (Kutsanedzie et al., 2020).

21.5 Silver nanoparticles for bacterial detection

1. Surface-enhanced Raman Spectroscopy (SERS)

Surface-enhanced Raman spectroscopy is a method of amplifying Raman signals using nanoscale metal surfaces. Such metallic nanosystems are called plasmonic nanoparticles, and when exposed to laser light, they exhibit different optical properties. AgNPs is used in amplifying (SERS) for detection of living bacteria such as *Salmonella* and *Staphylococcus aureus* (Liu et al., 2018). Monoclonal antibodies with high recognition capacity are used to target a specific surface protein of the bacteria (Lin et al., 2014).

2. Electrochemical biosensors

Electrochemical detection depends on the electrical current produced by oxidation or reduction of reactions to biological processes for the detection of molecular biomarkers from various pathogenic infections, a very sensitive method showed an accuracy (Sismaet and Goluch, 2018). In particular within the range of 1–10 nm, silver nanoparticles may interact with the surface of some gram-negative bacteria,

disturbing its functioning and inducing a bactericidal effect (Sepunaru et al., 2015). Because of the high affinity of silver nanoparticles to the bacteria surface, this concept was used to decorate bacteria with silver nanoparticles about 10 nm in diameters (Wu et al., 2018). A carbon fiber electrode was used to measure the chronoamperometric response of the silver nanoparticles.

3. Fluorescence methods

Fluorescence immunoassay is a highly sensitive technique for measuring mainly proteins and for quantifying antigens from viruses or bacteria as well as many other substances (Colino et al., 2018). The monoclonal antibody of *Pseudomonas aeruginosa* was appended to labeled AgNP with a pyrimidine fluorescent derivative. Due to the features of the metallic nanoparticle, the fluorescence response was able to enhance the metal surface when the fluorophore was located near it. This nanosystem is used for the identification of bacteria in water, crop samples, soil, and various food types (Li et al., 2011).

21.5.1 Mycotoxin detection

Nanoscale material displayed physicochemical properties differing from its larger counterpart due to a high area-to-volume ratio leading to increased reactivity (Borase et al., 2015). A single portable nanosensor can be fitted with thousands of nanoparticles to detect correctly harmful spores of the fungus, trace pollutants, and food toxins in a short period (Handford et al., 2014).

More than 300 mycotoxins were detected, and the serious effects of these toxins on animal and human health have been recorded (Lizárraga-Paulín et al., 2011). Analysis of mycotoxins is important and essential to ensure food safety because of the serious health risks associated with the presence of mycotoxins in food and its impact on domestic and international trade (Rhouati et al., 2017).

Due to the low cost, simplicity, and convenience of these methods, metal nanoparticules' colorimetric assays have received considerable attention. Furthermore, the manufacture of aptasensors depends on nanomaterials that play a role in the detection of toxins, amplifying the signal, mediating, and labeling the artificial enzyme (Rhouati et al., 2017).

The AgNPs have been widely used to detect analytes of mycotoxins (Velu and DeRosa, 2018). AgNPs demonstrated an efficient way of testing mycotoxin ochratoxin (OAT) concentration depending on the optical method of color detection (Velu and DeRosa, 2018). Nanosilver has found aptasensing applications as a signal amplifier to detect a wide range of molecules (Bahrami et al., 2016). AgNPs were also used to detect ochratoxin mycotoxin as aptamer carriers or as signal producing probes for aptasensing (Rhouati et al., 2017). Also, Chen et al. (2014) used a DNA-scaffolded-silver-nanocluster (AgNCs) as a fluorophore for the detection of OTA fluorescent. Also, the importance of silver nanoparticles in electro-oxidation and determination of aflatoxin M1 in milk samples was asserted (Shadjou et al., 2018).

21.5.2 Mycotoxin management

A quarter of cereal-based crops worldwide are contaminated with filamentous fungi and their mycotoxins and must be rejected at the expense of food supplies to a steadily increasing world population (WHO, 2018). Climate change contributes to worsening the situation further (Van de Perre et al., 2015). Fungi that produce mycotoxins are of paramount importance. Aflatoxins (*Aspergillus*), trichothecenes and fumonisins (*Fusarium*), alternariol and tenuazonic acid (Alternaria), and *Penicillium ochratoxins*, patulin and citrinin, are among the most important mycotoxins (Mukherjee et al., 2016). The most important mycotoxins are aflatoxins (AFs), ochratoxin A (OTA), fumonisins, trichothecenes, and zearalenones (JECFA, 2017). The widely distributed mycotoxigenic fungi, which cause risk on human health, are *Aspergillus ochraceus*, *Aspergillus niger*, *Aspergillus flavus*, *Aspergillus carbonarius,* and *Aspergillus parasiticus* (JECFA, 2018). The application of nanoparticles, e.g., as spray-disinfectant, could be an effective opportunity to avoid food and feed contamination due to mycotoxigenic fungi (Mittal et al., 2015).

Nutritional supplements may suppress mycotoxin toxicity, reduce tissue damage caused by oxidative stress, and enable the body to maintain a functional immune system that can eliminate the pathogens (Stroka and Maragos, 2016). Nanotechnology methods seem to be a promising, efficient, and low-cost way of reducing mycotoxins health effects (Horky et al., 2018). Recently, Mousavi and Pourtalebi (2015) showed that silver nanoparticles could severely inhibit the production of AFB1 aflatoxins at a dose of 135 $\mu g\,mL^{-1}$. Also, honey-derived silver nanoparticles showed a decrease in aflatoxin production to 66.5% and an inhibitory effect of ochratoxin production to 79.8% (El-Desouky and Ammar, 2016). Also, silver nanoparticles applied to *Aspergillus flavus* and *Aspergillus ochraceus* showed a reduction of mycotoxins aflatoxins (AFs) and ochratoxin A (OTA) production (Khalil et al., 2019).

AgNPs demonstrated superior antibacterial against *Staphylococcus aureus*, antifungal against *Aspergillus flavus* and *A. parasiticus* activities, and decreased the production of aflatoxins as opposed to Fe-NPs and Cu-NPs (Asghar et al., 2018). Three different sizes of citrated silver-coated nanoparticles inhibit aflatoxin biosynthesis at various effective doses of *Aspergillus parasiticus*, the pathogenic filamentous fungus of the plant (Mitra et al., 2019). Also, the AgNPs demonstrated notable antifungal activity against *Aspergillus flavus* and ability to thwart the production of mycotoxin (Khalil et al., 2019). AgNPs alone or as an active ingredient could be a good strategy for managing the main aflatoxigenic and ocratoxigenic species that affect contamination of food and aflatoxins (AFs) and ochratoxin A (OTA) (Gómez et al., 2019). Also, *Juniperus procera* leaf extract at 100 $mg\,mL^{-1}$ showed a growth inhibition of 35.83% and 44.09% but increased to 50.55% and 59.06% after 50 ppm silver nanoparticles (AgNPs) were added to *Aspergillus fumigatus* and *Fusarium chlamydosporum*, respectively (Bakri et al., 2020).

21.6 Conclusion and future perspectives

The application of large quantities of microbial pesticides and the presence of new microbial-resistant strains are the major critical concerns for food safety. This study depends on the use of NPs as an antifungal factor and antibacterial against the pathogens of plants as a new and successful tool for future prevention and control of pathogens, since bacteria and fungus are highly resistant to conventional control methods. We are therefore close to implementing modern agricultural techniques and new emerging technologies to more carefully and precisely manage these threats because traditional agricultural practices cannot adequately regulate these threats without jeopardizing human health. Effective NP biocidal can influence beneficial and deleterious bacteria, fungi, and other microorganisms under laboratory and environmental conditions, in particular, in soils and plants. AgNPs were found to regulate a wide variety of bacterial, fungal pathogens, and viral infections based on these findings. AgNPs may interfere with the replication, growth, and development of pathogens, thereby stopping or dying.

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