

Review

# Biological Synthesis of Silver Nanoparticles and Prospects in Plant Disease Management

Moh Tariq <sup>1,2,\*</sup>, Khan Nazima Mohammad <sup>2,†</sup>, Bilal Ahmed <sup>3,\*</sup>, Mansoor A. Siddiqui <sup>2</sup> and Jintae Lee <sup>3</sup>

<sup>1</sup> Department of Botany, Lords University, Alwar 301028, India

<sup>2</sup> Section of Plant Pathology and Nematology, Aligarh Muslim University, Aligarh 202002, India; khannazima160@gmail.com (K.N.M.); mansoor\_bot@yahoo.co.in (M.A.S.)

<sup>3</sup> School of Chemical Engineering, Yeungnam University, Gyeongsan 38541, Korea; jtlee@ynu.ac.kr

\* Correspondence: aziztariq14@gmail.com (M.T.); bilal22000858@yu.ac.kr (B.A.)

† These authors contributed equally to this work.

**Abstract:** Exploration of nanoparticles (NPs) for various biological and environmental applications has become one of the most important attributes of nanotechnology. Due to remarkable physico-chemical properties, silver nanoparticles (AgNPs) are the most explored and used NPs in wide-ranging applications. Also, they have proven to be of high commercial use since they possess great chemical stability, conductivity, catalytic activity, and antimicrobial potential. Though several methods including chemical and physical methods have been devised, biological approaches using organisms such as bacteria, fungi, and plants have emerged as economical, safe, and effective alternatives for the biosynthesis of AgNPs. Recent studies highlight the potential of AgNPs in modern agricultural practices to control the growth and spread of infectious pathogenic microorganisms since the introduction of AgNPs effectively reduces plant diseases caused by a spectrum of bacteria and fungi. In this review, we highlight the biosynthesis of AgNPs and discuss their applications in plant disease management with recent examples. It is proposed that AgNPs are prospective NPs for the successful inhibition of pathogen growth and plant disease management. This review gives a better understanding of new biological approaches for AgNP synthesis and modes of their optimized applications that could contribute to sustainable agriculture.

**Keywords:** silver nanoparticles; sustainable agriculture; plant disease; pathogen; green synthesis

**Citation:** Tariq, M.; Mohammad, K.N.; Ahmed, B.; Siddiqui, M.A.; Lee, J. Biological Synthesis of Silver Nanoparticles and Prospects in Plant Disease Management. *Molecules* **2022**, *27*, 4754. <https://doi.org/10.3390/molecules27154754>

Academic Editor: Mohammed Baalousha

Received: 26 May 2022

Accepted: 22 July 2022

Published: 25 July 2022

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

Phytopathogenic microbes and plant pests are natural inhabitants of the plant's surrounding environment and cause huge crop losses with a worldwide estimated reduction in crop production of 20–40% on an annual basis [1]. Applications of pesticides including fungicides and insecticides are currently being used [2] on a very large scale and are considered a key to pest management. The use of chemical pesticides is a rapid killing strategy against pathogenic microorganisms; however, their overuse and long-term persistence in soils unwantedly reduce soil fertility [3] and disrupt the natural micro and macro soil biota. Among them, many plant-beneficial microbes are either killed or their natural ecology is compromised. This necessitates the development of alternative strategies to control plant diseases. In this regard, nanotechnology seems to be an alternative; it has also progressed significantly in the field of medicine, e.g., as alternative antimicrobials [4–6] and pharmacology, e.g., for drug delivery. However, it has attracted relatively less support in precision agriculture [7]. We have seen significant progress in fabrication of NPs with unique functions and dimension-based physicochemical characteristics [8]. Owing to their astonishing properties, NPs with sizes 20–100 nm have received greater attention [9]. The sector of nano-enabled products tries, at their scale, to re-evaluate the biomass assets of previously reported anti-pathogenic substances to alter or inhibit the deadly effects of plant pathogens. Appropriate stimulants seem to be NPs with

polymers, metals, or porcelain that can show different biological use depending on their intensification.

NPs play a pivotal role in crop development and improving the nutritive benefits in the agricultural field. The NPs can be used as components of novel fertilizers in agriculture [10], substances for crop protection [11], herbicides [12], and preparations for prolonging cut flower durability [13]. NPs and nanomaterials have recently been proposed as potential biostimulators that could help plants propagate and grow faster [14,15] and develop plant resistance against oxidative stress [16]. The use of NPs could provide several advantages to agriculture and horticulture, but it may pose significant hazards due to their unrecognized environmental consequences [17]. However, detection of optimized concentrations of AgNPs for plant disease management without losing the efficiency and while keeping the non-toxicity of AgNPs to other non-target organisms can be achieved. This can be done through rigorous research on AgNPs selection for particular plant or pathogen species and the local conditions. The development and continuous improvement of AgNPs to regulate plant growth, soil quality, diseases, agrochemical usage, and environmental degradation have substantially strengthened soil quality, crop yield, and ecosystem security, which contribute greatly to sustainable farming and agro-ecosystems [18]. The utilization of agricultural inputs to speed up the site-specific monitored supply of nutrients enhances the crop productivity while assuring the minimization of the use of agri-input. This can be done with the help of engineered AgNPs; that is, with or without other agents that have their physicochemical properties. Along with the help for plant security solutions they offer, agro-nanotechnology has been actively improved, and this may ensure increased plant growth. Indeed, in the current and future crop promotion programs, nanotechnology has incredible potential to control pests and diseases.

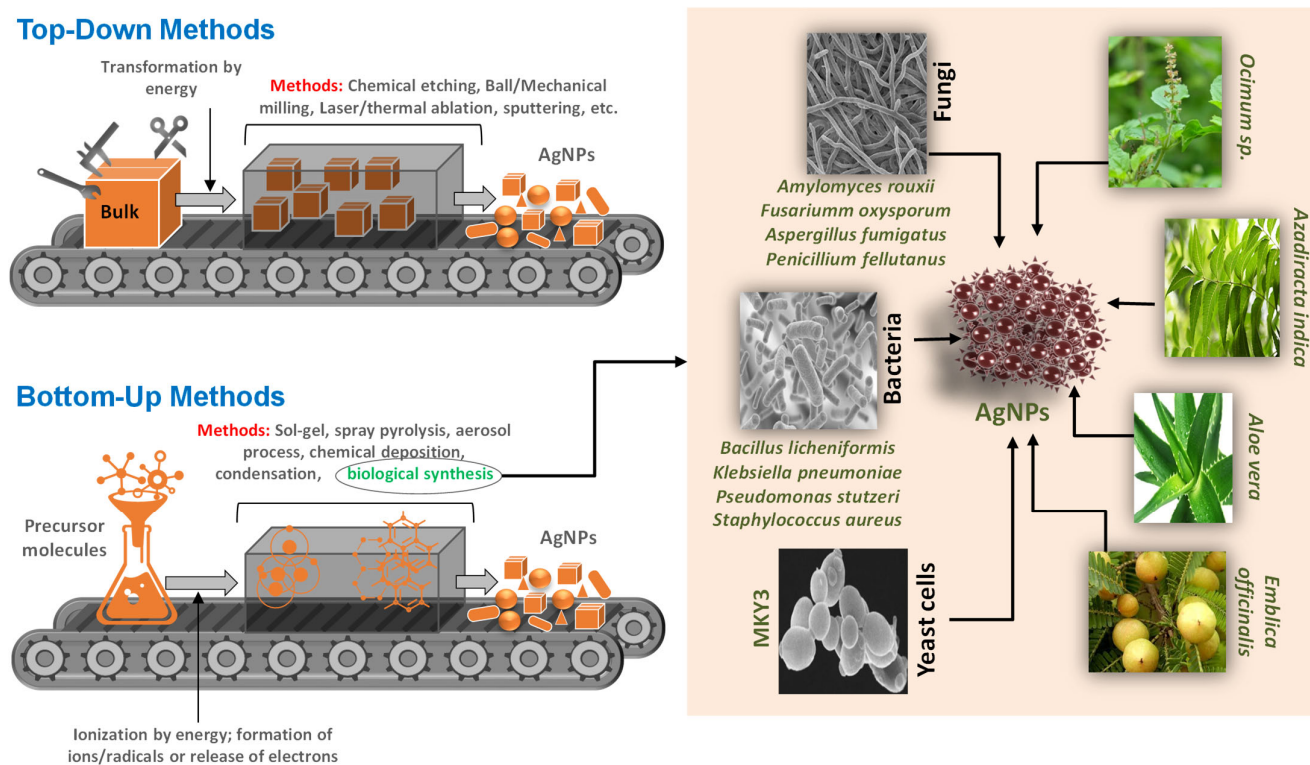
Different kinds of metal-based NPs have flourished, including copper (Cu), zinc (Zn), titanium (Ti), magnesium (Mg), gold (Au), and silver (Ag). Various structured AgNPs have been widely utilized for antimicrobial applications and disease prevention for hundreds of years. The physicochemical and structural heterogeneity of AgNPs is generally achieved by manipulating three important parameters: concentrations of reactants, temperature, and pH [19]. In the majority of studies reporting biological synthesis of AgNPs, silver nitrate ( $\text{AgNO}_3$ ) has been used as the source of silver ions, at 1 mM concentration [20,21]. However, some studies have reported the production of smaller-sized AgNPs when moderate [22] to lower [23] concentrations of  $\text{AgNO}_3$  were used. The temperature is yet another decisive factor that has a significant influence on the time consumed, rate of synthesis, and the stability of the size and properties of AgNPs [24,25]. The pH also control the size and shape of AgNPs, where acidic pH of the reaction medium yields larger-sized AgNPs (Binupriya et al., 2010) than the alkaline pH, as reported for *Epicoccum nigrum* cell filtrate-mediated synthesis of AgNPs [26]. Another example of pH-induced size variability of AgNPs is *Penicillium oxalicum*-mediated fabrication of AgNPs over a pH range of 5–13, where alkaline pH (12) produced lower size (4 nm) of AgNPs, consuming less time for synthesis [27]. This suggests higher and longer-term stability in AgNPs, which could be due to the electrostatic repulsion of ions [27]. Similarly, reaction of  $\text{AgNO}_3$  (1 mM) with *Capsicum annum* extract at pH 9 showed the maximum yield of biologically capped AgNPs [28].

The antimicrobial actions of AgNPs to plant pathogens can be defined as their properties to hinder or eliminate the growth of plant pathogens without damaging neighboring plant tissues [29]. AgNPs appear to be the most intriguing of metal NPs that exhibit adequate biological activity [30]. They have a wide range of beneficial effects on plants at certain concentrations [31] and arrest the growth of associated pathogenic fungi [32]. AgNPs have been shown to boost germination [33], growth exultation [34], vegetative growth [14], shoot induction, proliferation [14], and pigmentation [35]. Generally, three processes including physical, chemical, and biological processes are employed to prepare AgNPs. Physical and chemical approaches are typically found to be costly and environmentally unfriendly. However, biologically produced AgNPs exhibit great yield, good

solubility, and excellent stability for prolonged periods. Out of these three, the biological approach has remained as the simplest, environmentally far less toxic, commercially viable and mostly a single step approach that does not require thermal gradients, pressures, forces, or synthetic chemicals [36]. Biosynthesis of AgNPs through plant parts (i.e., leaf or bark or root or stem, or flower extracts) and microorganisms (i.e., from extra or intracellular molecules of fungi, algae, bacteria) is thus a great tool for simplifying their use in agriculture. This review summarizes the recent progress made in the biosynthesis of AgNPs and discusses the potential of AgNPs in various antibacterial, antifungal, antinematic, and antiviral applications from a plant disease perspective.

## 2. Biosynthesis of AgNPs

There are two primary approaches for the synthesis of NPs, (i) the top-down approach and (ii) the bottom-up approach, which are graphically presented in Figure 1. In the top-down approach, techniques like mechanical milling, etching, electro explosion, sputtering, and laser ablation are used. The bottom-up approach involves the use of superficial fluid synthesis, plasma spraying synthesis, aerosol process, laser pyrolysis, and green synthesis. In green biological methods, plants and microbial constituents are used as essential bio-reducing agents, which also provide versatility in AgNPs synthesis. Biological methods are considered more effective, inexpensive, sustainable, and environmentally non-toxic compared to chemical and physical methods since the biological materials are easily available and require no or less prior processing [37]. Generally, plant and microbially biosynthesized AgNPs are used as a source that can either be processed extracellularly or intracellularly [38]. Moreover, algae, fungi, and beneficial bacteria that can tolerate toxic materials, e.g., heavy metals and organic chemicals, while retaining the capacity of producing organic and inorganic reducing agents may be the biological solution for AgNPs synthesis.



**Figure 1.** Illustration of two approaches of synthesis of AgNPs in left panel: (i) top-down approaches such as mechanical, chemical, and electro-explosion, etc. In bottom-up approaches, inorganic or or-

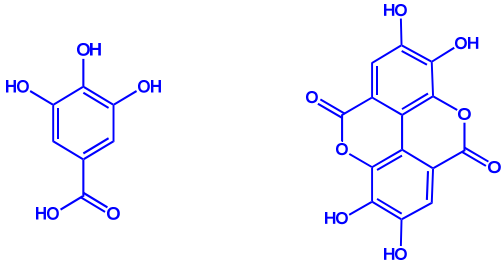
ganic substances are used as a reducing or capping agents. In bottom-up approaches, various techniques, i.e., superficial fluid synthesis, aerosol process, green synthesis (using bacteria, algae, fungi and plant or their biological products) etc. are used. Right panel shows a few proven examples of microbes and plants for AgNPs synthesis.

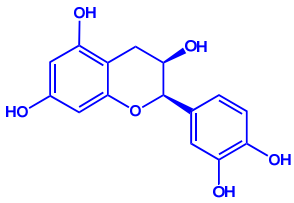
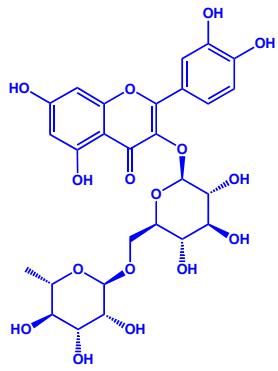
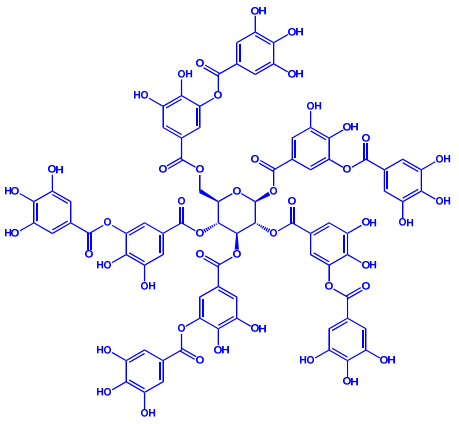
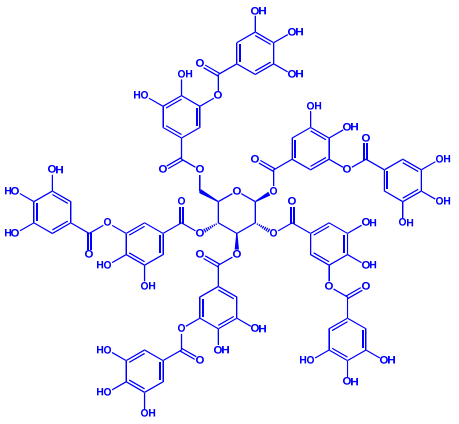
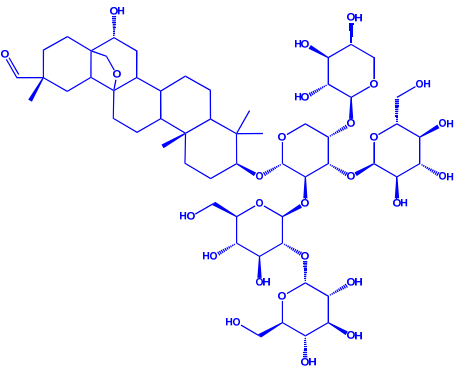
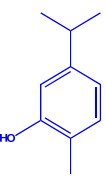
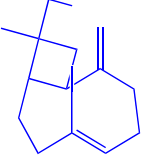
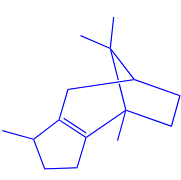
Based on the available literature, a general mechanism of AgNPs formation and growth can be suggested. Functional groups of biomolecules, such as those from polyphenols, release electrons in the reaction medium that interact with the molar concentrations of metal salt (generally  $\text{AgNO}_3$ ), and reduction of silver ions ( $\text{Ag}^+$ ) occur. As a result of reduction, particle formation begins and surface plasmon resonance (SPR) increases with a gradual to sharp intensification of dark color of the medium. At some point, the increase in SPR does not increase further and further reduction of  $\text{Ag}^+$  ions does not occur, which could be due to two major reasons (i) reduction of all available  $\text{Ag}^+$  ions by reducing agents and/or (ii) lack of adequate electrons in the medium, i.e., low concentration of biomolecules. The reduced atoms of silver ( $\text{Ag}^0$ ) then start to form aggregates that could be limited to a certain size if the capping agent is present in the reaction medium; otherwise, smaller aggregates further grow and form larger aggregates. The capping of  $\text{Ag}^0$  generally involves Van der Waals forces, electrostatic attraction, or covalent bond formation between capping agents and  $\text{Ag}^0$  atoms, and the AgNPs particle or crystal attains its characteristic size and shape.

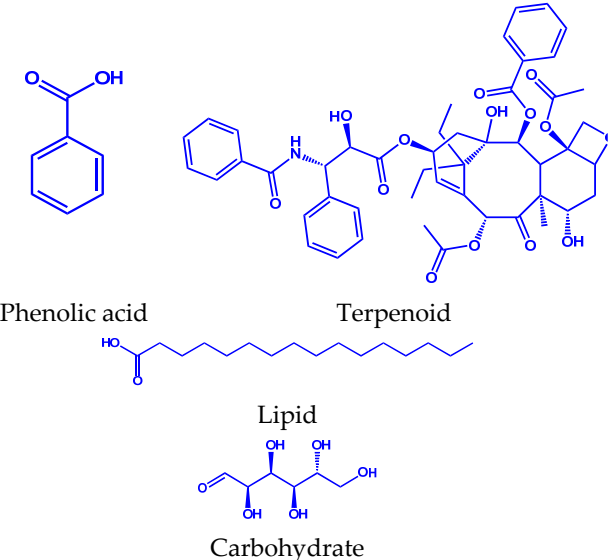
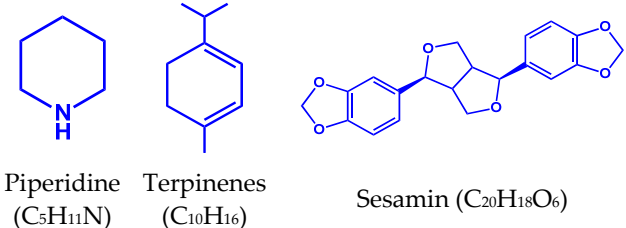
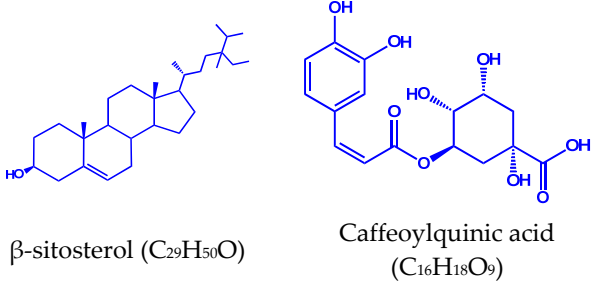
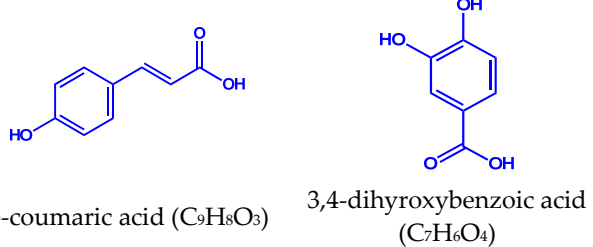
### 2.1. Biological Synthesis of AgNPs by Plant Parts

For the synthesis of AgNPs, plant parts such as leaves, fruits, stems, roots, seeds, and flowers are used due to their abundant quantity and availability, and their biochemical composition is also generally considered non-toxic to humans or other non-target organisms since they are known for producing beneficial phytochemicals. Several plants such as *Acacia nilotica*, *Ocimum sanctum*, *Coleus aromaticus*, *Lantana camara*, and *Moringa oleifera* have been used for AgNPs biosynthesis. Plant-derived AgNPs are characterized by various techniques [28], and based on their properties and need, are implemented in agricultural applications (Table 1 and Figure 2). Plants are widely available as the source of many rich metabolites that serve as bio-agents to reduce the  $\text{Ag}^+$  ions [39]. Biomolecules from several plant species may also be used for the coating of AgNPs in order to reduce the need of chemical reagents and hazardous substances or other approaches for purification [40]. *Eucalyptus globulus* [19], *Azadirachta indica* [41], *Cissus quadrangularis* [42], *Lantana camara* flower [43], *Rubus illecebrosus* leaf [44], *Nephelium lappaceum* peel [45], *Ricinus communis* [46], *Calotropis gigantea* are yet other species used in the green synthesis of AgNPs [47]. Reducing and stabilizing agents in plants help shape biocompatible AgNPs. Available secondary compounds including terpenoids, flavonoids, phenols, alkaloids, proteins, and carbohydrates in the extract function as reduction agents [48–51].

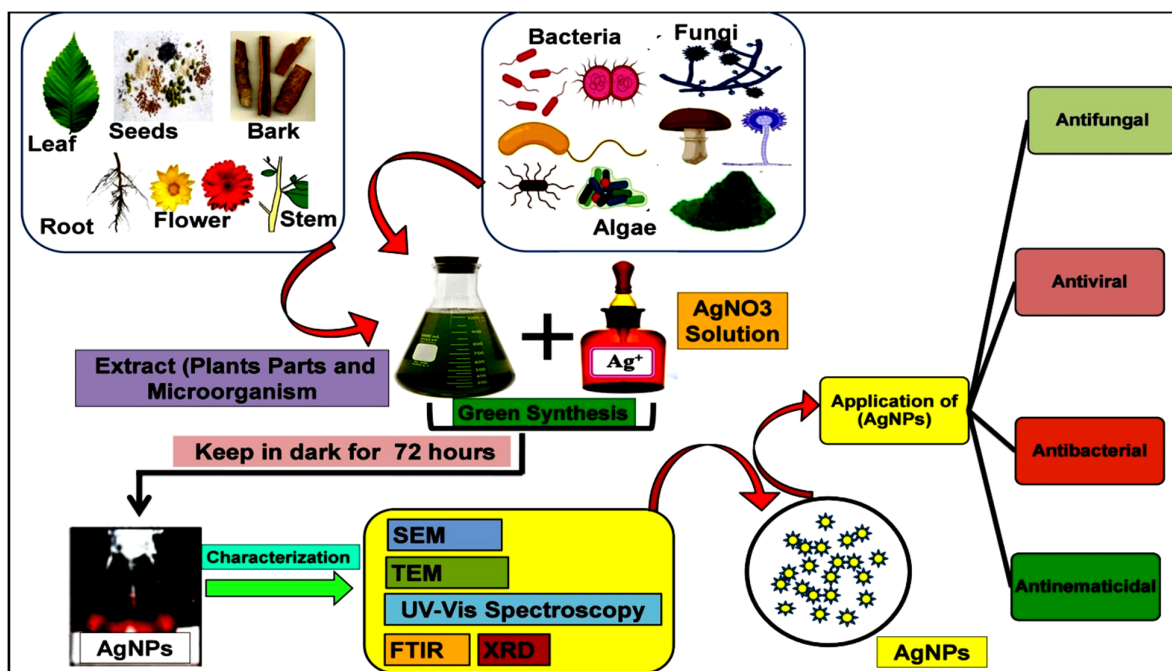
**Table 1.** Biological synthesis of AgNPs from various plant species.

Plants	Family	Plant Part	Metabolites and Their Structures	Corresponding Particle Size	Ref.
<i>Acacia nilotica</i>	Fabaceae	Pod		20–30 nm	[52]

			Gallic acid (C <sub>7</sub> H <sub>6</sub> O <sub>5</sub> )	Ellagic acid (C <sub>14</sub> H <sub>6</sub> O <sub>8</sub> )		
						
			Epicatechin (C <sub>15</sub> H <sub>14</sub> O <sub>6</sub> )	Rutin (C <sub>27</sub> H <sub>30</sub> O <sub>16</sub> )		
						
<i>Ocimum sanctum</i>	Lamiaceae	Fresh leaves	Tannins (tannic acid; C <sub>76</sub> H <sub>52</sub> O <sub>46</sub> )		15.72 nm	[53]
						
			Saponin (C <sub>58</sub> H <sub>94</sub> O <sub>27</sub> )			
<i>Coleus aromaticus</i>	Lamiaceae	Fresh leaves				44 nm [54]
			Carvacrol (C <sub>10</sub> H <sub>14</sub> O)	Caryophyllen (C <sub>15</sub> H <sub>24</sub> )	Patchoulene (C <sub>15</sub> H <sub>24</sub> )	

<i>Lantana camara</i>	Verbenaceae	Fresh leaves	 <p>Phenolic acid</p> <p>Terpenoid</p> <p>Lipid</p> <p>Carbohydrate</p>	14–27 nm	[55]
<i>Piper longum</i>	Piperaceae	Dried fruit	 <p>Piperidine (C<sub>5</sub>H<sub>11</sub>N)</p> <p>Terpinenes (C<sub>10</sub>H<sub>16</sub>)</p> <p>Sesamin (C<sub>20</sub>H<sub>18</sub>O<sub>6</sub>)</p>	15–200 nm	[56]
<i>Moringa oleifera</i>	Moringaceae	Fresh stem bark	 <p><math>\beta</math>-sitosterol (C<sub>29</sub>H<sub>50</sub>O)</p> <p>Caffeoylquinic acid (C<sub>16</sub>H<sub>18</sub>O<sub>9</sub>)</p>	40 nm	[57]
<i>Syzygium cumini</i>	Myrtaceae	Air dried seeds	 <p>p-coumaric acid (C<sub>9</sub>H<sub>8</sub>O<sub>3</sub>)</p> <p>3,4-dihydroxybenzoic acid (C<sub>7</sub>H<sub>6</sub>O<sub>4</sub>)</p>	40–100 nm	[58]



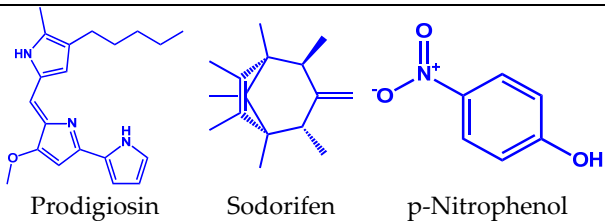
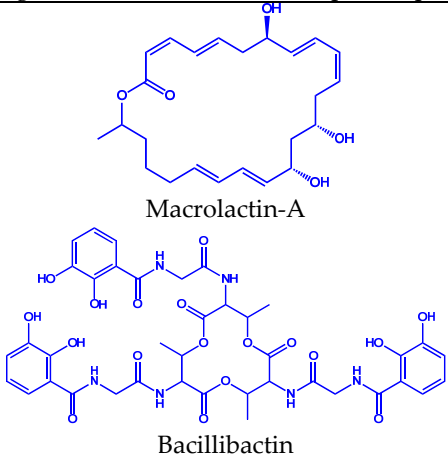
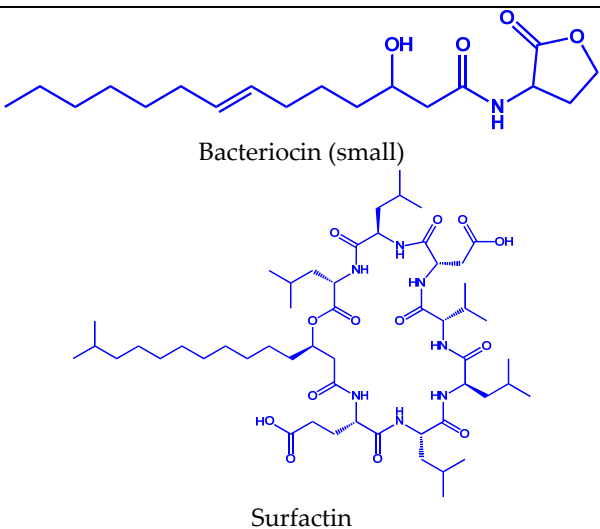
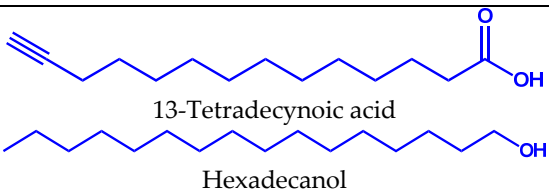
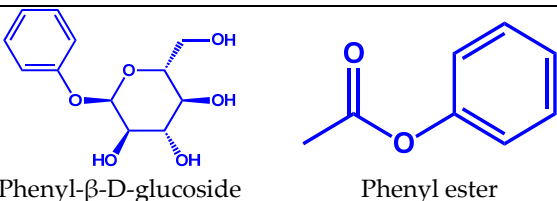


**Figure 2.** Illustration of green synthesis of AgNPs from various extracts such as plant parts (i.e., stem, leaf, flower, barks, seeds, and root) and microorganisms. Prepared extracts of known dilutions are mixed with predefined molarity of silver nitrate ( $\text{AgNO}_3$ ) solution and stirred/kept under dark conditions for a fixed time, e.g., 72 h. Following harvest, the AgNPs are physicochemically characterized for size, shape, and surface area, charged by techniques such as transmission electron microscopy (TEM), scanning electron microscopy (SEM), UV-Vis spectroscopy, FTIR, XRD, DLS, and zeta-potential, etc., and applied for several purposes such as removal of bacteria, fungi, viruses, or nematodes.

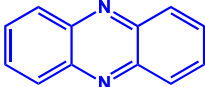

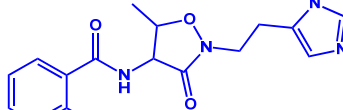
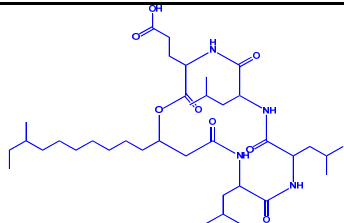
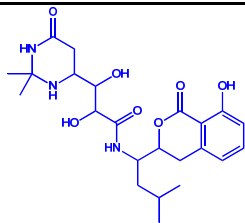
## 2.2. Biological Synthesis of AgNPs by Bacteria

Biological preparation of AgNPs through microbes has been recognized as a rapidly growing field of research in green nanotechnology. Different microbial entities have constantly been engaged in the synthesis of AgNPs, which are seen as alternatives to the traditional chemical and physical strategies. Many bacterial species such as *Serratia nematodiphila*, *Bacillus stearothermophilus*, *Escherichia coli*, *Morganella morganii* RP42, *Pseudomonas proteolytica*, *P. meridiana*, *B. brevis*, etc. were used in AgNPs biosynthesis (Table 2 and Figure 2). Moreover, several other microorganisms, including *B. methylotrophicus*, *Brevibacterium frigoritolerans*, and *Novosphingobium* sp., have recently been found effective for the production of AgNPs. Mechanistically, bacteria are responsible for secreting different enzymes in broth culture that include several reductases that perform AgNPs biosynthesis [59]. In the process, bacterial cells act as reducing entities because they extracellularly induce the nucleation and capping of NPs by reducing metal ions ( $\text{Ag}^+$ ) to metal NPs (AgNPs) [60]. Bacteria can offer comprehensive opportunities for the synthesis of AgNPs because of their reasonably easy cultivation process and quick replication efficiency. *Pseudomonas stutzeri* (AG259) was the first bacteria to be used for the synthesis of AgNPs [59]. The AgNPs were also synthesized using *Bacillus* species like *B. megaterium* (NCIM 2326), *B. cereus*, *B. licheniformis*, *B. amyloliquefaciens*, *B. marisflavi*, *B. flexus*, and *B. subtilis* [61].

**Table 2.** Biological synthesis of AgNPs by various bacterial strains.

Bacterial Strains	Metabolites	Structure	Size	References
<i>Serratia nematodiphila</i>	(a) Prodigiosin (b) Sodorifen (c) p-Nitrophenol, etc.	 Prodigiosin      Sodorifen      p-Nitrophenol	65–70 nm	[61]
<i>Bacillus steatothermophilus</i>	(a) Macrolactin-A (b) Bacillibactin, etc.	 Macrolactin-A Bacillibactin	14 nm	[62]
<i>Bacillus strain CS11</i>	(a) Bacteriocin (b) Surfactin, etc.	 Bacteriocin (small) Surfactin	42–92 nm	[63]
<i>Escherichia coli</i>	(a) 13-Tetradecynoic acid (b) Hexadecanol, etc.	 13-Tetradecynoic acid Hexadecanol	NA	[64]
<i>Morganella morganii</i> RP42	(a) Phenyl-β-D-glucoside (b) Phenyl ester, etc.	 Phenyl-β-D-glucoside      Phenyl ester	10–50 nm	[65]

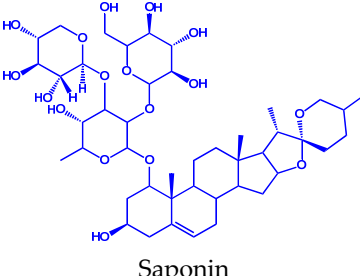
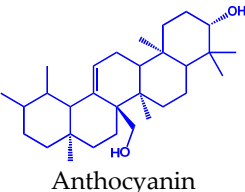


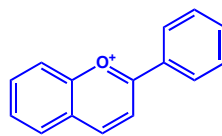
<i>Pseudomonas proteolytica</i> and <i>Pseudomonas merdiana</i>	(a) Phenazines		Phenazine		Hydrogen cyanide	4–13 nm	[66]
	(b) Hydrogen cyanide		Pseudomonine				
	(c) Pseudomonine, etc.						
<i>Bacillus brevis</i> (NCIM 2533)	(a) Bacilotettrine		Bacilotettrine		Hetiamacin	68 nm	[67]
(b) Hetiamacin, etc.							

### 2.3. Biological Synthesis of AgNPs by Algae and Fungi

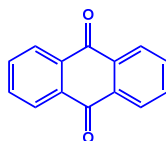
Among other organisms, algae, a group of marine or freshwater microorganisms, are widely considered as bio-nano factories as both live and dead dried biomasses have been used to synthesize NPs [68]. In addition to algae, fungi also play a significant role in the green synthesis of AgNPs. Algae and fungi serve as reducing agents and function in an environmentally friendly way for sustainable and non-toxic fabrication of AgNPs. The majority of the algae used for this purpose are from the species of *Sargassum plagiophyllum*, *Chlorococcum humicola*, *Amphora-46*, *Caulerpa racemose*, *Padina pavonica*, and *Chaetomorpha linum* etc., and mycelium of fungi, i.e., *Aspergillus fumigates*, *Penicillium fellutanum*, *A. flavus*, *Fusarium semitectum*, and *Alternaria alternata* (Table 3 and Figure 2). Fungal molecules based AgNPs are unique over bacteria in terms of providing higher rates of growth of organism, easy cultivation methods and high levels of extracellular enzyme secretions, increased NPs tolerance (protein coating), and excellent stability with high concentrations of NPs [69]. Massive fungal flora have recently had major research involvement in synthesizing suitable biocompatible AgNPs including *Trichoderma resei*, *A. niger*, *F. oxysporum*, and *Phytophthora infestans* [70]. For instance, owing to its biologically active substances that have antimicrobial antioxidant, immunomodulating, and anti-cancer properties, *Penicillium oxalicum* have certain benefits in biogenic synthesis [70]. Other fungi like *F. oxysporum*, *F. semitectum*, *F. acuminatum*, *F. solani*, *Cladosporium cladosporioides*, and *T. asperellum* can also synthesize AgNPs with a broad range of applications [71].

**Table 3.** Biological synthesis of AgNPs by various strains of algae and fungi.

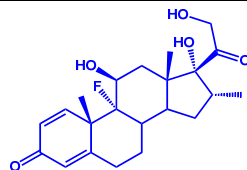
Algae	Metabolites	Structure	Size	References
<i>Sargassum plagiophyllum</i>	(a) Saponins (b) Anthocyanins (c) Triterpenes, etc.	 	18–42 nm	[64]



Triterpene



Anthraquinone



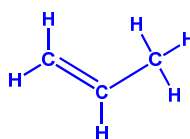
1-propene

4–6  
nm

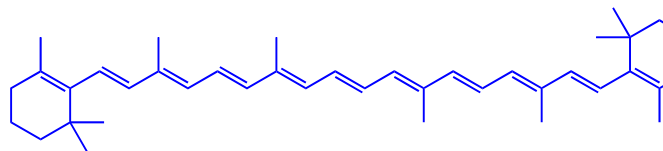
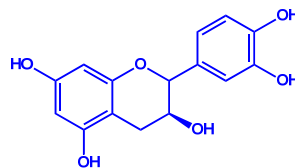
[72]

*Chlorococcum hu-*  
*micola*

(a) Anthraquinone  
(b) Steroids  
(c) 1-propene, etc.



Steroid

 $\beta$ -carotene

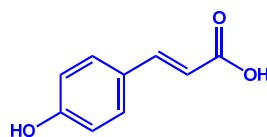
Catechin

5–70  
nm

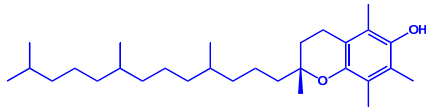
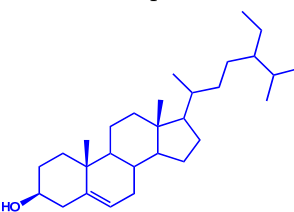
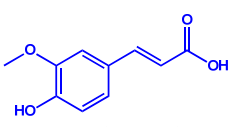
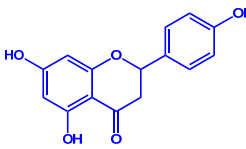
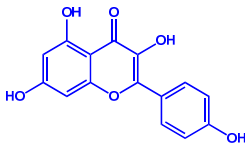
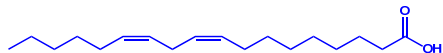
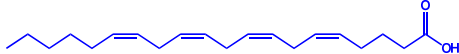
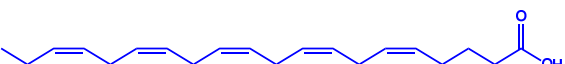
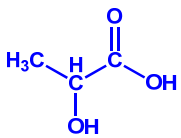
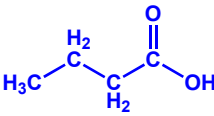
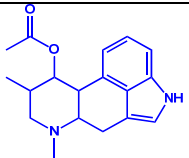
[73]

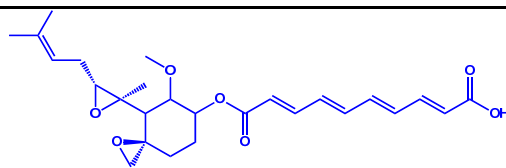
*Amphora-46*

(a)  $\beta$ -carotene  
(b) Catechin  
(c) p-coumaric acid,  
etc.

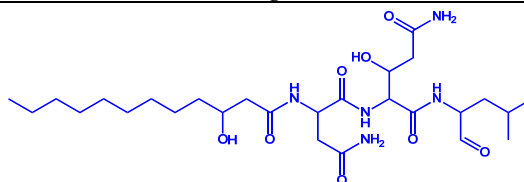


p-coumaric acid

<i>Caulerpa racemosa</i>	(a) $\alpha$ -tocopherol (b) $\beta$ -sitosterol, etc.	 $\alpha$ -tocopherol  $\beta$ -sitosterol	5–25 nm [74]
<i>Padina pavonica</i>	(a) Ferulic acid (b) Naringenin (c) Kaempferol, etc.	 Ferulic acid  Naringenin  Kaempferol	10–72 nm [75]
<i>Chaetomorpha linum</i>	(a) Linoleic acid	 Linoleic acid	
	(b) Arachidonic acid	 Arachidonic acid	3–44 nm [76]
	(c) Eicosapentaenoic acid, etc.	 Eicosapentaenoic acid	
<i>Gelidium amansii</i>	(a) Lactic acid (b) Butyric acid, etc.	 Lactic acid  Butyric acid	27–54 nm [77]
<i>Aspergillus fumigatus</i>	(a) Fumigaclavine (b) Fumagillins, etc.	 Fumigaclavine	5–25 nm [78]



Fumagillins



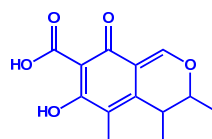
Fellutamide

*Penicillium fellu-*  
*tanum*

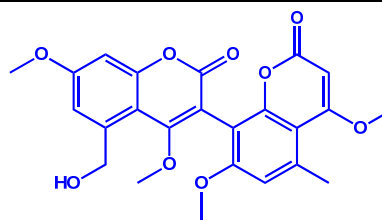
(a) Fellutamide  
(b) Citrinin, etc

5–25  
nm

[79]



Citrinin

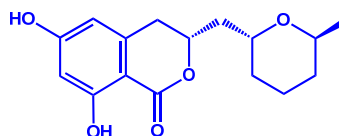


Aflavarin

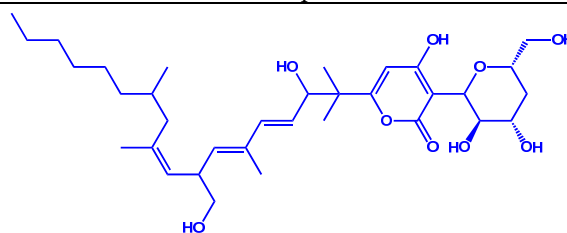
*Aspergillus flavus*  
(a) Aflavarin  
(b) Cladosporin, etc.

8.92  
nm

[80]



Cladosporin

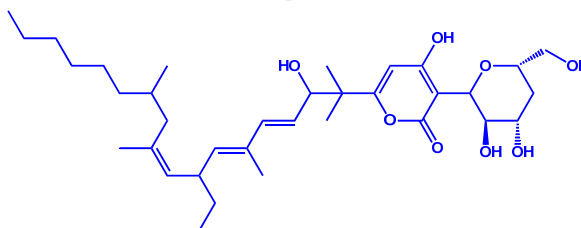


Fusapyrone

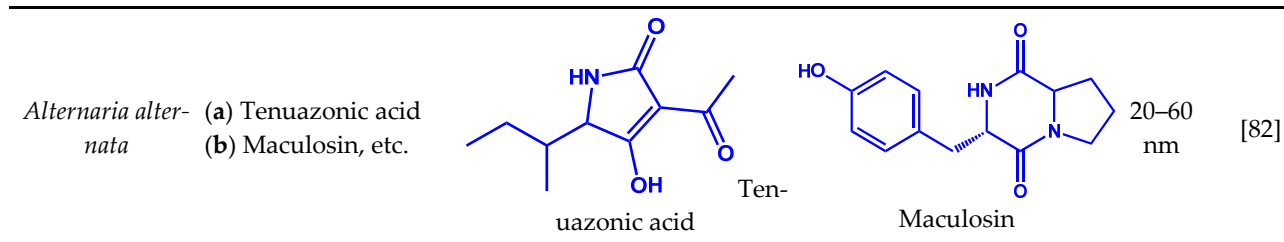
*Fusarium semitec-*  
*tum*  
(a) Fusapyrone  
(b) Deoxyfusapyrone,  
etc.

10–60  
nm

[81]



Deoxyfusapyrone



### 3. Determining the Size, Shape and Yield of Biological AgNPs

Determining the shape and size of biologically synthesized AgNPs is the most relevant aspect of AgNPs synthesis since it also determines the interfacial reactions with organisms and intracellular penetration of AgNPs. This can be fine-tuned by optimizing the hydrogen ion concentration of the medium. For example, *Aloe vera* extract mixed at variable pH with solvent resulted in variously sized and shaped Au–Ag core NPs [83]. In most studies, AgNPs have been successfully synthesized at room temperature [84,85], while a few studies also report the control of their shapes by temperature [86]. Regarding shapes, low reaction temperature yielded the formation of nano-triangle AgNPs while high temperature produced spherical AgNPs using *Cymbopogon flexuosus* extract as reducing and capping agent [87]. When plant biomass is used, some physical and chemical parameters control the crystal growth and structure of NPs [88], for instance, the amount/percentage of the metal salt solution. In fact, for near-perfect control over the size and shape of AgNPs, reaction parameters such as concentrations of metal ions and extracts, duration of the reaction, temperature, and pH are adjusted in a series of different reactions [89,90]. Moreover, the biological production of AgNPs is also governed by enzymatic reaction. For example, in a study, Korbekandi et al. showed pre-incubation of *Fusarium oxysporum* with 0.1 mM AgNO<sub>3</sub> for the activation of reducing enzymes. Additionally, glucose added as electron donor helped in the reduction of AgNPs. The optimized values for four parameters were: 0.1 mM AgNO<sub>3</sub> as inducer of enzymes, 5 mM AgNO<sub>3</sub> as substrate, amount of biomass (4.96 g dry weight/L), and 56 mM glucose as electron donor. The use of microbes, algae, and plants for biological synthesis of AgNPs is widely known and has been optimized with several species [91]. However, the green synthesis method is faster and more feasible compared to algae mediated or microbial synthesis. This is possibly due to the easy availability of plant materials that do not require maintenance as in the case of microbes. Plant materials are available in plenty, and since plants have a bigger genome size and more complex physiology, the biomolecular composition of plants is far better in terms of their variety and quicker production of AgNPs. AgNPs produced through green routes are generally more biocompatible and stable [92,93].

## 4. Silver Nanoparticles in Plant Disease Management

### 4.1. AgNPs in Bacterial Disease Management

The antimicrobial properties of AgNPs are significant for a wide range of microorganisms including bacteria, fungi, and viruses [94]. AgNPs measuring 10–100 nm in size have a strong antibacterial effect against several Gram-positive and Gram-negative bacteria [95]. AgNPs are well-known to be effective antimicrobials against multidrug-resistant (MDR) bacteria, such as methicillin-resistant *Staphylococcus aureus*, erythromycin-resistant *Streptococcus pyogenes*, ampicillin-resistant *E. coli*, and vancomycin-resistant *S. aureus* [96]. In a study, AgNPs prepared using *Azadirachta indica* extract inhibited the growth of phytopathogens *Penicillium* sp., *Aspergillus* sp., *Fusarium* sp., and *Ralstonia solanacearum* [32]. Silver ions prevent bacterial DNA replication by linking and causing denaturation of the DNA, which involves silver ion interaction with thiol proteins accompanied by DNA condensation, which leads to apoptosis [97]. The antibacterial activity of AgNPs is largely due to the release of silver cations, which can bind bacterial proteins specifically to thiol (-SH) groups and interrupt their physiological functions [98], leading to necrobiosis. AgNPs

carry out their antibacterial activities via a Trojan horse mechanism: their preliminary attachment to the surface of the cell leads to modification and degradation of cell membrane, and release of intracellular metal silver ions exerts toxicity [99]. AgNPs showed pronounced inhibition of growth of *E. coli*, *P. aeruginosa*, and *S. aureus* [100]. The antibacterial effects of AgNPs are mostly due to their broad surface layers, which allow for greater contact between the NPs and microbial cells, suppressing cell development at very low concentrations present in surroundings [101]. The weaker susceptibility to NPs of Gram-negative bacteria (i.e., *E. coli*) can even be clarified due to the presence of an external lipopolysaccharide (LPS) coating on their surface that restricts the penetration of compounds. However, elevated concentrations of antibacterial agents are therefore required to achieve the same effect on Gram-positive bacteria [102]. AgNPs rely mostly on size, shape, surface functionalization, and ability to display certain antimicrobial properties [103]. The bactericidal impact is also thought to result from the AgNP-mediated generation of reactive oxygen species (ROS) [104]. Two potential AgNP toxicity mechanisms have been explored [105]. One is that AgNPs have a large bacterial surface contact that can enable the cellular membranes to bind to the particles and penetrate effectively into the bacteria. Another mechanism is the interference of AgNPs or dissolved ions with the respiratory chain of cell membrane. Much evidence demonstrates that the antibacterial activities of AgNPs include silver ions [106,107].

To date, some processes have been demonstrated, including protein disruption [108], ROS production and antioxidant degradation, membrane disability work (e.g., membrane disruption, lack of membrane permeability), mutagenicity, and transport protein gene expression downregulation [109]. Membrane fluidity and metabolic activities are disrupted as a result of the morphological changes of cellular membranes impacted by AgNPs and membrane depolarization, which eventually leads to cell component damage and even death. The leakage of molecules inside the cell, such as enzymes, proteins, metabolites, and DNA, is caused by the breakdown of cellular structures. Furthermore, AgNP can form unusual holes in microbial cell walls, allowing NPs to penetrate extracellular and intracellular areas [110]. TEM may be used to study the behavior of AgNP-induced membrane damage and perforation of cell membranes [98]. In recent studies, TEM shows extensive cell surface disintegration, nuclear and cytoplasmic material leaking, and enlargement of cells [111,112]. Moreover, the antibacterial mechanism of AgNPs can follow a dual mode of action of particles and silver ions [113,114]. Some recent examples of inhibition of growth of bacterial pathogens are listed in Table 4.

**Table 4.** AgNPs in bacterial disease management.

AgNP Types	Size (nm)	Pathogen(s)	Effect(s)	Reference
AgNPs	25 to 50	<i>Xanthomonas oryzae</i> pv. <i>Oryzae</i> strain LND0005 and <i>Acidovorax oryzae</i> strain RS-1	Inhibited bacterial growth, biofilm formation	[115]
AgNPs	-	<i>Bacillus subtilis</i> and <i>Escherichia coli</i>	Suppressed the growth of pathogens	[116]
AgNPs	7 and 25	<i>Edwardsiella tarda</i> and <i>E. coli</i>	Antibacterial activity	[117]
AgNPs	27	<i>P. aeruginosa</i> and <i>S. marcescens</i> .	Antibacterial activity	[117]
AgNPs	-	<i>Klebsiella pneumoniae</i> , <i>P. aeruginosa</i> , <i>S. marcescens</i> , <i>Streptococcus pyogenes</i> , and <i>Staphylococcus aureus</i>	In vitro activity against bacterial pathogens	[118]
AgNPs	-	<i>E. coli</i>	Suppressed biofilm formation	[119]
AgNPs	12	<i>Clavibacter michiganensis</i> subsp. <i>michiganensis</i> (Cmm)	Inhibited bacterial canker in tomatoes	[120]
AgCSs	15 to 25	<i>X. oryzae</i> pv. <i>oryzae</i>	In vitro activity against blight disease of rice	[121]

AgNPs	24.5	<i>R. solanacearum</i> strain YY06	Negatively affected bacterial growth, biofilm formation, swimming motility, induced cell membrane damage, and reactive oxygen species (ROS)	[122]
AgNPs	25 to 75	<i>E. coli</i> and <i>S. aureus</i>	Applied as antibacterial material for fruit and vegetable preservation	[123]
AgNPs	18 to 39	<i>X. oryzae</i> pv. <i>oryzae</i>	Increased the plant biomass with a decreased levels of cellular ROS	[124]
AgNPs	470	<i>X. phaseoli</i> pv. <i>phaseoli</i>	Growth inhibition	[125]

#### 4.2. AgNPs in Viral Disease Management

In agriculture, AgNPs can be used as antivirals. Viruses are assumed to be involved in almost 50% of all evolving plant diseases, which seem to be difficult to manage; there is no cure in some situations. Viral infections necessitate appropriate and effective management. The viral multiplication cycle includes viral replication into cells, genomic and viral biosynthesis, viral component assembly, and emission of virus particles from the host cell [126]. AgNP's potential antiviral mechanisms include interactions with gp120, antagonistic impact on virus attachment to the cell, destruction of virus particles before entry, and interaction of AgNPs with double-stranded DNA [127]. AgNPs can also interact with the polypeptide coats of tomato mosaic virus (ToMV) and potato virus Y (PVY) [128]. Resulting from interactions with envelope glycoproteins, AgNPs directly inactivate TMV, causing immediate damage to TMV shell proteins, agglomeration, and even disintegration. Elbeshehy et al. [129], studied AgNPs fabricated from *Bacillus persicus*, *B. pumilus*, and *B. licheniformis*; the AgNPs had a negative influence on the yellow bean mosaic virus. A post-infection treatment given 24 h after virus exposure inhibited the virus from causing any detrimental manifestations. Plants treated with AgNPs and inoculated simultaneously showed only mild BYMV symptoms, and a 72-h pre-infection treatment had almost no influence on viral concentration or disease severity. When AgNPs were applied on *Chenopodium amaranticolor* crops 24 h after treatment, they displayed the most substantial antiviral impact against tomato spot wilt virus (TSWV). Plants sprayed after inoculation had a poor infection, but plants treated before inoculation had a weak inhibition [130]. El-shazly et al. [131] reported that potato plants sprayed with AgNPs 24 h after being inoculated with tomato bushy stunt virus (TBSV) showed a decrease in virus concentration and disease percentage [131]. *Cymopsis tetragonaloba* leaves sprayed with AgNPs and sun hemp rosette virus (SHRV) showed full disease reduction by suppressing virus replication [132]. When compared to individual AgNPs and salicylic acid (SA) treatments, a combination of AgNPs and SA administered before 3 and 7 days of virus infection had a synergistically antiviral impact against TBSV [131]. Because the NPs attached to the virus and hindered viral replication, spraying AgNPs on infected tomatoes for 7 days before treatment with ToMV and PVY reduced disease severity and virus concentration [128].

The expression of antioxidant enzymes POD (peroxidase) and polyphenol peroxidase (PPO) in tomato plants treated with AgNPs and infected with ToMV or PVY increased significantly [128]. Mahfouze et al. [133] discovered that banana plants infected with BBTV and treated with 50 ppm AgNPs did not exhibit any outward symptoms, even though the infection rate was 36%. On the other hand, banana plants treated with 50 ppm AgNPs following viral infection showed a considerable improvement in dry weight and leaf area when compared to BBTV-infected banana plants (viral control). When compared to the healthy control, all plants treated with 50 ppm AgNPs after virus inoculation had considerably higher levels of phenol, proline, and oxidative enzymes. Elbeshehy et al.



[129] studied the effect of biosynthesized AgNPs on BYMV-infected fava bean leaves and displayed significant symptoms such as yellow mosaic, mottling, crinkling, size reduction, and deformation, which were not present in non-infected leaves. According to Jain and Kothari [132], AgNPs sprayed over the bean leaves showed 100% suppression of the sun-hemp rosette virus. Cai et al. [134] asserted that antiviral activity of NPs in plants is due not only to inhibition of virus replication, but is also responsible for the stimulation of defense mechanisms in plants that contribute to plant immunity and growth response. For example, AgNPs stimulated a phytohormone cytokinin in *Capsicum annuum* L. [135]. Tripathi et al. [136] suggested that AgNPs adsorption in plants might hinder apoplastic transportation of virus particles by obstructing cell connections, the plasmodesmata, and preventing the apoplastic movement of liquid and nutrients. Hassan et al. [137] employed RAPD and direct amplification of minisatellite-region DNA (DAMD) approaches to detect DNA modification in olive plants exposed to varying concentrations of silver or selenium nanoparticles. They observed that 5 mg L<sup>-1</sup> AgNPs had a positive effect on in vitro performance. However, 10 mg L<sup>-1</sup> AgNPs and 2.5 and 5 mg L<sup>-1</sup> SeNPs induced changes on genomic DNA level. In addition, RAPD and DAMD assays can be successfully applied as a sensitive method of detecting DNA stability and genotoxicity in olive plants treated with different concentrations of selenium and silver NPs. Mahfouze et al. [133] demonstrated that after BBTV infection, the banana plants sprayed with different concentrations of AgNPs showed a few changes at the genomic DNA level, whereas both random amplified polymorphic DNA (RAPD) and sequence-related amplified polymorphism (SRAP) markers scored nearly the same polymorphism in the banana plants (Table 5).

**Table 5.** AgNPs in viral disease management.

AgNP Types	Size (nm)	Plant	Pathogen	Effect(s)	References
AgNPs	10–20	<i>Cymopsis tetragonaloba</i>	Sunhemp Rosette Virus (SHRV)	Complete suppression of the disease	[132]
AgNPs	77	<i>Vicia faba</i>	Bean Yellow Mosaic Virus (BYMV)	Decrease in virus concentration, percentage of infection and disease severity, reduction in lesions on infected leaves	[129]
AgNPs	12	<i>Solanum tuberosum</i>	Potato Virus Y (PVY)	Resistance to virus infection	[131]
Graphene oxide-silver NPs (GO-AgNPs)	30–50	<i>Lactuca sativa</i>	Tomato Bushy Stunt Virus (TBSV)	Decrease in virus concentration, infection percentage, and disease severity	[138]
AgNPs	12.6	<i>Solanum tuberosum</i> L. cv. <i>Spunta</i>	Tomato Spotted Wilt Virus (TSWV)	Decrease in TSWV infectivity and produces an inhibitory effect in local lesions	[130]
AgNPs	-	<i>Solanum lycopersicum</i>	Tomato Mosaic Virus (ToMV) Potato Virus Y (PVY)	Reduction in disease severity and virus infection	[128]
AgNPs	-	Autotrophic plants	Banana Bunchy Top Virus (BBTV)	Inhibition of apoplastic trafficking by blocking pores and barriers in the cell wall or plasmodesmata	[136]
AgNPs		<i>S. tuberosum</i>	Potato Virus Y (PVY)	Induced resistance to virus	[138]
Schiff base AgNPs		<i>N. tabacum</i>	Tobacco Mosaic Virus (TMV)	Induced resistance to virus by promoting plant immunity	[139]

#### 4.3. AgNPs in Fungal Disease Management

The utilization of AgNPs as an alternative to synthetic fungicides has been a relatively new approach with more efficacy. AgNPs may be used for the control of plant diseases as part of their implementation. A few studies have been performed so far on the implementation of AgNPs against phytopathogenic fungi [140]. The latest anti-fungal agents are often in demand because of the development of resistance in pathogenic fungi [141]. There have been cases of antifungal resistance globally, which favor the emergence of resistant mutants due to frequent applications of agrochemicals that also alters the fungal population [142,143]. AgNPs synthesized using *A. flavus* inhibited the growth of *Trichoderma* spp. [144]. The AgNPs also showed antifungal properties against *Candida albicans* and *C. tropicalis* [145] and *F. oxysporum* [146]. Due to enhanced permeability and retention effects, the AgNPs seem to be very attractive and fascinating for diverse anti-fungal applications. Recently, more work has been directed towards developing safe management strategies, which placed humans and animals at lower risk and concentrate on resolving synthetic fungicide vulnerabilities. Nanotechnology represents a way of developing new antifungal secondary metabolites to reduce the symptoms caused by emerging resistant fungi [147]. AgNPs have several antifungal action mechanisms, involving linkages to DNA phosphates groups [148] and plasma–membrane interactions, that contribute to proton dispersion and cell mortality, sulfhydryl protein and enzyme groups, degradation of the electron transportation chain, and disturbance of membrane proton motive force and phosphate groups [149].

AgNPs have been shown to have a wide range of antifungal properties, including against aggressive fungal infections [150] such as *C. albicans*, *C. tropicalis*, *C. parapsilosis*, *C. glabrata* [151], *Trichophyton rubrum* [152], *Trichosporona sahii* [153], *A. niger*, *Rhizoctonia solani*, *Curvularia lunata*, *Colletotrichum* sp., and *Fusarium* sp. [154,155]. DNA impairs the fungal culture's ability to proliferate after it has been treated with silver crystals (AgCs) [156]; this may result in decreased protein expression in the subunit as well as faulty enzymes and cellular proteins required for ATP generation [157]. Several other plant fungi, such as *Alternaria alternata* and *Trichosporona sahii*, have shown similar effects with AgNPs. The production of reactive oxygen species (ROS) can cause NP toxicity [153]. Free radicals can damage cell walls, proteins, lipids, and DNA, among other biological components. Deletions, mutations, single strand rupture, double-strand breakage, and protein cross-linking are all examples of DNA damage [158] (Table 6).

**Table 6.** AgNPs in fungal disease management.

Nanoparticles	Size (nm)	Pathogen	Effect	References
AgNPs	50.6	<i>Helminthosporium rostratum</i> , <i>Fusarium solani</i> , <i>F. oxysporum</i> and <i>Alternaria alternata</i>	Effectively mitigated the mycelial growth	[159]
AgNPs	10–12	<i>F. chlamydosporum</i> and <i>Aspergillus flavus</i>	Suppressed the growth of pathogens	[160]
OT-AgNPs	5–61	<i>F. oxysporum</i> , <i>A. niger</i> , and <i>A. flavus</i>	Antifungal ability	[161]
AgNPs	15	<i>Candida albicans</i>	Suppressed the growth of pathogens	[162]
AgNPs	25.6	<i>A. terreus</i> Thom	Retardation in fungus growth and biomass	[163]
AA.AgNPs and SD.AgNPs	8–52 and 5–45	<i>A. niger</i> , <i>A. flavus</i> and <i>F. oxysporum</i>	Highly antifungal effect against pathogens	[164]
AgNPs	-	<i>F. oxysporum</i>	Antifungal activity	[165]
AgCSs	-	<i>Aspergillus</i> sp.	Abnormal spore germination and distorted hyphae	[166]

AgNPs	47	<i>Colletotrichum gloeosporioides</i>	Controlled black anther infection during storage of cut orchid flowers	[167]
MC.AgNPs and PG.AgNPs	5–29 and 5–53	<i>A. niger</i> , <i>A. flavus</i> and <i>F. oxysporum</i>	Inhibitory action	[168]
AgNPs		<i>A. fumigates</i> , <i>A. niger</i> , <i>A. flavus</i> , <i>Trichophyton rubrum</i> , <i>C. albicans</i> , and <i>Penicillium sp.</i>	Inhibition of fungal growth and biofilm	[169]
AgNPs	100	<i>M. phaseolina</i> , <i>S. sclerotiorum</i> , and <i>D. longicolla</i>	Inhibited the growth of fungi	[170]

#### 4.4. AgNPs in Nematode Disease Management

Various crops are annually damaged by more than 4100 species of plant pathogenic nematodes [171]. Therefore, the development of new nematicides with lessened side effects on non-target organisms and the environment is critical. Recently, evidence has shown that AgNPs have effective nematocidal potential [172,173]. According to different studies, AgNPs can decrease the nematode infestation through the pretreatment of plant seedlings. Researchers also suggest that AgNPs have a direct toxic effect on nematodes and may result in reproduction inhibition [174]. For this to occur, generation of excessive oxidative stress may be an important mechanism in AgNPs toxicity to nematodes [175]. AgNPs exposure in *Caenorhabditis elegans* decreased reproductive potential and increased ROS formation, expression of the phosphomevalonate kinase (PMK-1/p38), MAPK (Mitogen-Activated Protein Kinases), hypoxia-inducible factor (HIF-1), and glutathione S-transferase (GST) enzyme activity [174]. Degradation in the cell wall of *Meloidogyne incognita* second-stage larvae (J2) was also observed due to AgNP toxicity under lab conditions [176].

A study on micro-crystalline cellulose-embedded AgNPs reported that a dose of 20–40 ppm caused deflection during the growth stages and influenced embryogenesis eggs' hatchability and survival in J2 of *M. incognita* [173]. In another study, AgNPs synthesized from *Artemisia Judaica* extracts caused an increase in juvenile mortality and egg hatch inhibition in comparison to crude extracts [177]. Furthermore, AgNPs showed antinematic properties against *M. graminicola* in rice without adverse effects on seed germination or plant growth [172]. The anti-nematode primary mode of action of produced AgB-NPs inhibits several physiological pathways in nematode cells such as membrane permeability, ATP organization, and reaction to oxidative stress [174,178]. Structural immunization may be significantly affected by different characteristics such as disparities in cell wall composition and the production of phytochemicals and pathogenesis-related proteins [179]. Furthermore, phytoalexin organization is frequently connected to the resulting resistance stages of produced AgB-NPs [179]. As a response to nanoparticle stimuli, some plants produce a wide range of secondary metabolites, including phenol and other phytochemicals. They may be an important part of the plant's defense mechanism against insects such as root-knot nematodes [180]. Some studies on AgNPs effects on nematodes are summarized in Table 7.

Table 7. AgNPs in nematode disease management.

Nanoparticles	Size (nm)	Target Nematode	Test Crop	Effect	References
AgNPs	100	<i>Heterodera sacchari</i>	<i>Oryza sativa</i>	Decreased nematode population in the root and soil, improved vegetative development of the rice plant	[181]
AgNPs	15	<i>Meloidogyne incognita</i>	<i>Solanum nigrum</i>	Apart from nematode movement, impacts on production, embryogenesis, hatchability percentage, and larval stages were evident. Inhibition of J2 worms and prevention of egg hatching (in vitro). In vivo infestation of tomato roots was considerably decreased when a root dip therapy with AgNPs was used	[173]
Et-AgNPs	20–30	<i>M. incognita</i>	<i>S. lycopersicum</i>	Inhibition of eggs and 2nd juvenile (J2) stage of <i>M. incognita</i>	[182]
AgNPs	30–100	<i>M. incognita</i>	<i>S. melongena</i>	Vegetative growth and fruit weight were increased to varying degrees when the nematode population was diminished	[183]
AgNPs	2	<i>M. incognita</i>	<i>Arachis hypogea</i>	Antagonistic effect on the nematode eggs and larval stages	[181]
AgNPs	50–150	<i>M. incognita</i>	<i>S. lycopersicum</i>	Highest increase in growth parameters, as well as the minimum galls and egg masses	[177]
AgNPs	5–50	<i>M. incognita</i>	<i>S. lycopersicum</i>	A substantial reduction in the formation of root galls	[184]
AgNPs	20	<i>M. graminicola</i>	<i>O. sativa</i>	Drastically decreased egg hatching, increased larval mortality, diminished root galling, and J2 population in soils	[172]
AgNPs	16	<i>M. javanica</i>	Faba bean	Reduced second-stage juveniles (J2s), nematode population in soil, and enhanced growth characteristics	[185]
Green Silver Nanoparticles (GSN)	8–19	<i>M. javanica</i>	<i>S. melongena</i>	Increased turfgrass productivity in one year and reduced root gall development in two years without phytotoxicity	[186]
AgNPs	-	<i>M. incognita</i>	Bermuda grass	Significant reduction in the number of galls, egg masses, developmental stage, rate of build up, and nematode population in soil	[187]
AgNPs	5–10	<i>M. incognita</i>	<i>S. lycopersicum</i>	Increased the plant defense gene's expression (chitinase gene)	[176]
AgNPs	13.09 and 10.51	<i>M. javanica</i>	<i>S. lycopersicum</i>	Second-stage juvenile immobility and mortality	[188]
AgNPs	20	<i>M. incognita</i>	<i>S. lycopersicum</i>	Reduced the level of second-stage juveniles, females, and developmental stages while improving the host plant's resistance and immunity	[189]
Ag-BNPs	29.55	<i>M. incognita</i>	<i>S. lycopersicum</i>	Galls, egg masses, females per root system/plant, and juvenile mortality were all reduced, and the immune system was induced to resist against nematode infection	[190]
AgNPs	25 to 55	<i>M. incognita</i>	<i>S. lycopersicum</i>		[191]

#### 4.5. Mechanisms of AgNPs Mediated Inhibition or Killing of Phytopathogens

Despite plenty of reports on pathogen inhibition by AgNPs, the precise mode of antibacterial/antimicrobial action of AgNPs against phytopathogens is not completely understood. Here, we attempted to gather the available information on common modes of antimicrobial action of AgNPs. The AgNPs show their effects mainly by interacting with the cells as (i) particles and/or (ii) Ag<sup>+</sup> ions dissolved from applied AgNPs. Some studies have shown that AgNPs produce excessive intracellular ROS, induce an antioxidant response, and interact with

essential macromolecules. For instance, Hajipour et al. [108] reported protein disruption by AgNPs, while Lemire et al. [109] and Xia et al. [153] detected ROS induction by AgNPs and its degradation by cellular antioxidant machinery, which followed destability of membrane, genotoxicity, and inhibition of transporter gene expression. Free radicals (a form of ROS and also a part of free radical chain reaction) disrupts chemical bonding and structure of cell walls and biological molecules, including nucleic acids (i.e., DNA), fats, and proteins. Some of the examples of DNA damage are mutations, deletions, and single/double strand breaks [158]. The toxic outcome of AgNP treatment could be a combination of these effects against phytopathogens, since AgNPs may attack multiple cellular targets at once. This has been explained in many other studies [32,192–194]. In the process, AgNPs adhere to the cell membranes through electrostatic attraction, affect the morphology of membranes, and cause membrane depolarization, which makes the membrane more permeable. The AgNPs also inhibit cellular respiration and metabolic activity, leading to direct and/or collateral damage to cell components and induction of cell death. In doing so, the AgNPs overwhelm the microbes and the extensive breakdown of cellular components induces the leakage of essential cell fluids or substances (i.e., essential metabolites, proteins, and enzymes) within and/or outside the cell. The creation holes in membranes and walls of microbes by AgNPs facilitate the release of cell content into intracellular spaces and extracellular environment [110]. This kind of hole or perforation in membrane and on cell surface could be observed by transmission electron microscopy (TEM), and the leakage of cytoplasmic material and swelling was also confirmed by TEM. TEM exhibits severe disruption of cell walls, leakage of nuclear and cytoplasmic material, and swelling [111,112]. Similar effects were observed for the AgNP-treated fungi *Trichosporon asahii* and *Alternaria alternata* [153]. In a bacterium *Azotobacter vinelandii*, AgNPs caused cell membrane damage and were present inside the cells as observed by TEM. These AgNPs induced the formation of hydroxyl radicals in *A. vinelandii* cells that were detected by electron spin resonance [195]. Summarily, the sequence of events of AgNP interactions with phytopathogens can be described as (i) adherence of AgNPs to bacterial cell surfaces based on their charge and size of NPs, (ii) entry of AgNPs to cell interior or dissolution of Ag<sup>+</sup> ions from AgNPs, (iii) ROS generation by AgNPs in the inner membrane, (iv) excessive ROS causing oxidative burst and activating cellular components that further induce damage to membranes, (v) subsequent leakage of DNA and other cellular materials leading to cell death.

## 5. Biological AgNPs against Plant Pathogens: Possible Implications in Lab to Land Transfer

Several attempts are being made worldwide by nanotechnologists and microbiologist to improve traditional agriculture via the sustainable use of biologically synthesized AgNPs. The control over size, shape, and yield of AgNPs has been made more advanced due to technological innovations in synthesis and characterization processes of AgNPs. The AgNPs may aid the agricultural industry by combating pathogens and avoiding the plant disease incidences in a somewhat regulated and site-specific manner. In general, application of AgNPs to agriculture have a significant potential to improve agricultural productivity [35]. However, the impacts and fate of applied concentrations of AgNPs on agricultural systems as a whole are not fully defined. Therefore, greater public interest in adopting AgNP-based agricultural products for farming and knowledge of their benefits and issues associated with nano-enabled agricultural products will more likely trigger the awareness and acceptability. Since, nanotechnology is gaining impetus at a faster pace, it may become a crucial and most useful component of agriculture industry, the phototoxicity of synthesized AgNPs could be repressed by coating the powdered AgNPs with biocompatible materials such as polyvinyl pyrrole [196]. The toxicity and use cases of Ag-based nanomaterials and AgNPs have been well-established by the Environmental Protection Agency (EPA) [6,197]. In a report, it was claimed that the formulations of >100 pesticides contain AgNPs, which are incorporated as antimicrobial agents. However, there is a lack of information on their trophic transfer and toxicity to humans. Not all types of AgNPs are expected to be toxic. For example, a citrate-coated “colloidal” AgNP showed

no photo-, cyto-, or geno-toxicity to human cells, but its “powder” form was toxic [198]. This could be due to the chemical conversion of powder AgNPs silver oxides or release of silver ions. By using biocompatible materials [198], alternatives can be explored and researched to suppress the unwanted toxicity of AgNPs, and this could be accomplished by engineering AgNPs with biocompatible materials during their growth in the media or after the synthesis. Such biocompatible coatings or materials would certainly increase their effects, such as enhanced germination of seeds and plant growth. Sometimes, environmental factors also affect the morphology and physicochemical characteristics of NPs and may show different effects on different plant species in real soil environment or field conditions [199]. Therefore, one type of AgNPs cannot be the solution for all pathogens and safe for all host plant species. Maximum effectiveness from lab setups (controlled hydroponic, pot media, or soil) to land or field environments could only be achieved if one type of AgNP is optimized for use with one plant species, or a group of related species that face a similar pathogen attack and disease symptoms.

## 6. Environmental Relevance and Possible Toxicity of Biological AgNPs

Despite the well-defined anti-phytopathogenic effects of AgNPs, the harmful impacts or toxicity of AgNPs to non-target organisms or beneficial microbes of the eco-system cannot be denied while they are being used to regulate growth of causal organisms of plant diseases [11,98]. The interaction of AgNPs with organisms may vastly vary in each method of application, i.e., either foliar or soil application. Though the amount of AgNPs applied is low, there is the possibility that they may disperse from the agricultural soil to water and air. The dispersion modes can be surface run-off by rain or leaching to ground water [200]. Therefore, in agricultural applications of AgNPs, the prior knowledge of AgNPs toxicity to other organisms, especially the beneficial rhizoplane/rhizosphere and phylloplane microflora, should be obtained. Additionally, AgNPs have shown toxicity to some edible crop plants [199]. Therefore, only concentrations of AgNPs that are biologically specific to certain phytopathogens, while being safe for other organisms (especially the host plant), should be used.

## 7. Conclusions

Several strategies have been adopted over the last decade to improve the biological synthesis of AgNPs. Increased understanding and utilization of biological materials *viz.* plant parts, bacteria, and fungi have resulted in advantages over conventional approaches. The many reasons for this include eco-acceptability, cost-effectiveness, safety, and pharmaceutical compatibility without the involvement of hazardous chemicals/processes, high pressure, or energy. Biologically synthesized AgNPs provide significant nano-enabled features for broad-spectrum agricultural applications, specifically in plant pathogen inhibition, because they exert antibacterial, antifungal, and antinematic potential. The current review also highlights that AgNPs originating from green routes may also accumulate in the ecological niche; however, their expected risk to the microbiome and plants is variable.

Various green methods have been established for the production of anti-plant pathogen AgNPs with high yield, purity, and control over their shapes and sizes. Further research should be directed towards the selection of threshold concentrations of AgNPs that efficiently minimize disease instance or severity in plants without exhibiting detrimental impact on the non-target organisms and soil fertility. The physicochemical nature of produced AgNPs can be specific to one crop species and local environmental conditions.

**Author Contributions:** Conceptualization, M.T., K.N.M. and M.A.S.; writing—original draft preparation, M.T., K.N.M., B.A., and M.A.S.; writing—review and editing, B.A., J.L., and M.A.S.; visualization, M.T., and B.A.; supervision, M.A.S.; funding acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was funded by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2021R1G1A1094698) and Priority Research Centers Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2014R1A6A1031189).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The author M.T. is thankful to Department of Botany, Lords University, Alwar for providing necessary facilities to carry out this research work.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Savary, S.; Ficke, A.; Aubertot, J.-N.; Hollier, C. Crop Losses Due to Diseases and Their Implications for Global Food Production Losses and Food Security. *Food Secur.* **2012**, *4*, 519–537.
2. Shahid, M.; Ahmed, B.; Zaidi, A.; Khan, M.S. Toxicity of Fungicides to: *Pisum Sativum*: A Study of Oxidative Damage, Growth Suppression, Cellular Death and Morpho-Anatomical Changes. *RSC Adv.* **2018**, *8*, 38483–38498. <https://doi.org/10.1039/c8ra03923b>.
3. Shahid, M.; Ahmed, B.; Khan, M.S. Evaluation of Microbiological Management Strategy of Herbicide Toxicity to Greengram Plants. *Biocatal. Agric. Biotechnol.* **2018**, *14*, 96–108. <https://doi.org/10.1016/j.bcab.2018.02.009>.
4. Rani, P.; Ahmed, B.; Singh, J.; Kaur, J.; Rawat, M.; Kaur, N.; Matharu, A.S.; AlKahtanie, M.; Alhomaidif, E.A.H.; Lee, J. Silver Nanostructures Prepared via Novel Green Approach as an Effective Platform for Biological and Environmental Applications. *Saudi J. Biol. Sci.* **2022**, *29*, 103296.
5. Kaur, K.; Ahmed, B.; Singh, J.; Rawat, M.; Kaur, G.; AlKahtani, M.; Alhomaidi, E.A.H.; Lee, J. Bryonia Laciniosa Linn Mediated Synthesized Green Au NPs for Catalytic and Antimicrobial Applications. *J. King Saud Univ.* **2022**, *34*, 102022.
6. Janani, B.; Syed, A.; Raju, L.L.; Bahkali, A.H.; Al-Rashed, S.; Elgorban, A.M.; Ahmed, B.; Thomas, A.M.; Khan, S.S. Designing Intimate Porous Al<sub>2</sub>O<sub>3</sub> Decorated 2D CdO Nano-Heterojunction as Enhanced White Light Driven Photocatalyst and Antibacterial Agent. *J. Alloys Compd.* **2022**, *896*, 162807.
7. Sinha, K.; Ghosh, J.; Sil, P.C. New Pesticides: A Cutting-Edge View of Contributions from Nanotechnology for the Development of Sustainable Agricultural Pest Control. In *New Pesticides and Soil Sensors*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 47–79.
8. Arya, S.S.; Sharma, M.M.; Das, R.K.; Rookes, J.; Cahill, D.; Lenka, S.K. Vanillin Mediated Green Synthesis and Application of Gold Nanoparticles for Reversal of Antimicrobial Resistance in *Pseudomonas Aeruginosa* Clinical Isolates. *Heliyon* **2019**, *5*, e02021.
9. Jiang, B.; Li, C.; Dag, Ö.; Abe, H.; Takei, T.; Imai, T.; Hossain, M.; Shahriar, A.; Islam, M.; Wood, K. Mesoporous Metallic Rhodium Nanoparticles. *Nat. Commun.* **2017**, *8*, 1–8.
10. Elmer, W.H.; White, J.C. The Use of Metallic Oxide Nanoparticles to Enhance Growth of Tomatoes and Eggplants in Disease Infested Soil or Soilless Medium. *Environ. Sci. Nano* **2016**, *3*, 1072–1079.
11. Worrall, E.A.; Hamid, A.; Mody, K.T.; Mitter, N.; Pappu, H.R. Nanotechnology for Plant Disease Management. *Agronomy* **2018**, *8*, 285. <https://doi.org/10.3390/agronomy8120285>.
12. Maruyama, C.R.; Guilger, M.; Pascoli, M.; Bileschy-José, N.; Abhilash, P.C.; Fraceto, L.F.; De Lima, R. Nanoparticles Based on Chitosan as Carriers for the Combined Herbicides Imazapic and Imazapyr. *Sci. Rep.* **2016**, *6*, 1–15.
13. He, Y.; Qian, L.; Liu, X.; Hu, R.; Huang, M.; Liu, Y.; Chen, G.; Losic, D.; Zhu, H. Graphene Oxide as an Antimicrobial Agent Can Extend the Vase Life of Cut Flowers. *Nano Res.* **2018**, *11*, 6010–6022.
14. Saha, N.; Dutta Gupta, S. Promotion of Shoot Regeneration of *Swertia Chirata* by Biosynthesized Silver Nanoparticles and Their Involvement in Ethylene Interceptions and Activation of Antioxidant Activity. *Plant Cell Tissue Organ Cult.* **2018**, *134*, 289–300.
15. Thangavelu, R.M.; Gunasekaran, D.; Jesse, M.I.; SU, M.R.; Sundarajan, D.; Krishnan, K. Nanobiotechnology Approach Using Plant Rooting Hormone Synthesized Silver Nanoparticle as “Nanobullets” for the Dynamic Applications in Horticulture—an in Vitro and Ex Vitro Study. *Arab. J. Chem.* **2018**, *11*, 48–61.
16. Avestan, S.; Ghasemnezhad, M.; Esfahani, M.; Byrt, C.S. Application of Nano-Silicon Dioxide Improves Salt Stress Tolerance in Strawberry Plants. *Agronomy* **2019**, *9*, 246.
17. Feregrino-Perez, A.A.; Magaña-López, E.; Guzmán, C.; Esquivel, K. A General Overview of the Benefits and Possible Negative Effects of the Nanotechnology in Horticulture. *Sci. Hortic.* **2018**, *238*, 126–137.
18. Chen, Y.W.; Lee, H.V.; Juan, J.C.; Phang, S.-M. Production of New Cellulose Nanomaterial from Red Algae Marine Biomass *Gelidium Elegans*. *Carbohydr. Polym.* **2016**, *151*, 1210–1219.
19. Ali, K.; Ahmed, B.; Dwivedi, S.; Saquib, Q.; Al-Khedhairi, A.A.; Musarrat, J. Microwave Accelerated Green Synthesis of Stable Silver Nanoparticles with *Eucalyptus Globulus* Leaf Extract and Their Antibacterial and Antibiofilm Activity on Clinical Isolates. *PLoS ONE* **2015**, *10*, e0131178. <https://doi.org/10.1371/journal.pone.0131178>.
20. Rahman, S.; Rahman, L.; Khalil, A.T.; Ali, N.; Zia, D.; Ali, M.; Shinwari, Z.K. Endophyte-Mediated Synthesis of Silver Nanoparticles and Their Biological Applications. *Appl. Microbiol. Biotechnol.* **2019**, *103*, 2551–2569.



21. Flieger, J.; Franus, W.; Panek, R.; Szymańska-Chargot, M.; Flieger, W.; Flieger, M.; Kołodziej, P. Green Synthesis of Silver Nanoparticles Using Natural Extracts with Proven Antioxidant Activity. *Molecules* **2021**, *26*, 4986.
22. AbdelRahim, K.; Mahmoud, S.Y.; Ali, A.M.; Almaary, K.S.; Mustafa, A.E.-Z.M.A.; Hussein, S.M. Extracellular Biosynthesis of Silver Nanoparticles Using *Rhizopus Stolonifer*. *Saudi J. Biol. Sci.* **2017**, *24*, 208–216.
23. Phanjom, P.; Ahmed, G. Effect of Different Physicochemical Conditions on the Synthesis of Silver Nanoparticles Using Fungal Cell Filtrate of *Aspergillus Oryzae* (MTCC No. 1846) and Their Antibacterial Effect. *Adv. Nat. Sci. Nanosci. Nanotechnol.* **2017**, *8*, 45016.
24. Elamawi, R.M.; Al-Harbi, R.E.; Hendi, A.A. Biosynthesis and Characterization of Silver Nanoparticles Using *Trichoderma Longibrachiatum* and Their Effect on Phytopathogenic Fungi. *Egypt. J. Biol. Pest Control* **2018**, *28*, 1–11.
25. Jiang, X.C.; Chen, W.M.; Chen, C.Y.; Xiong, S.X.; Yu, A.B. Role of Temperature in the Growth of Silver Nanoparticles through a Synergetic Reduction Approach. *Nanoscale Res. Lett.* **2011**, *6*, 1–9.
26. Qian, Y.; Yu, H.; He, D.; Yang, H.; Wang, W.; Wan, X.; Wang, L. Biosynthesis of Silver Nanoparticles by the Endophytic Fungus *Epicoccum Nigrum* and Their Activity against Pathogenic Fungi. *Bioprocess Biosyst. Eng.* **2013**, *36*, 1613–1619.
27. Du, L.; Xu, Q.; Huang, M.; Xian, L.; Feng, J.-X. Synthesis of Small Silver Nanoparticles under Light Radiation by Fungus *Penicillium Oxalicum* and Its Application for the Catalytic Reduction of Methylene Blue. *Mater. Chem. Phys.* **2015**, *160*, 40–47.
28. Ahmed, B.; Hashmi, A.; Khan, M.S.; Musarrat, J. ROS Mediated Destruction of Cell Membrane, Growth and Biofilms of Human Bacterial Pathogens by Stable Metallic AgNPs Functionalized from Bell Pepper Extract and Quercetin. *Adv. Powder Technol.* **2018**, *29*, 1601–1616. <https://doi.org/10.1016/j.apt.2018.03.025>.
29. Panja, A.; Mishra, A.K.; Dash, M.; Pandey, N.K.; Singh, S.K.; Kumar, B. Silver Nanoparticles—A Review. *Eurasian J. Med. Oncol.* **2021**, *5*, 95.
30. Zhang, X.-F.; Liu, Z.-G.; Shen, W.; Gurunathan, S. Silver Nanoparticles: Synthesis, Characterization, Properties, Applications, and Therapeutic Approaches. *Int. J. Mol. Sci.* **2016**, *17*, 1534.
31. Mehmood, A. Brief Overview of the Application of Silver Nanoparticles to Improve Growth of Crop Plants. *IET Nanobiotechnol.* **2018**, *12*, 701–705.
32. Haroon, M.; Zaidi, A.; Ahmed, B.; Rizvi, A.; Khan, M.S.M.S.; Musarrat, J. Effective Inhibition of Phytopathogenic Microbes by Eco-Friendly Leaf Extract Mediated Silver Nanoparticles (AgNPs). *Indian J. Microbiol.* **2019**, *59*, 273–287. <https://doi.org/10.1007/s12088-019-00801-5>.
33. Parveen, A.; Rao, S. Effect of Nanosilver on Seed Germination and Seedling Growth in *Pennisetum Glaucum*. *J. Clust. Sci.* **2015**, *26*, 693–701.
34. Jasim, B.; Thomas, R.; Mathew, J.; Radhakrishnan, E.K. Plant Growth and Diosgenin Enhancement Effect of Silver Nanoparticles in *Fenugreek (Trigonella Foenum-Graecum L.)*. *Saudi Pharm. J.* **2017**, *25*, 443–447.
35. Latif, H.H.; Ghareib, M.; Tahon, M.A. Phytosynthesis of Silver Nanoparticles Using Leaf Extracts from *Ocimum Basilicum* and *Mangifera Indica* and Their Effect on Some Biochemical Attributes of *Triticum Aestivum*. *Gesunde Pflanz.* **2017**, *69*, 39–46.
36. Ge, L.; Li, Q.; Wang, M.; Ouyang, J.; Li, X.; Xing, M.M.Q. Nanosilver Particles in Medical Applications: Synthesis, Performance, and Toxicity. *Int. J. Nanomed.* **2014**, *9*, 2399.
37. Biradar, D.; Lingappa, K.; Dayanand, A. Antibacterial Activity of Nano Goldparticles Synthesized by *Bacillus Sps.* *J. Ecobiotechnol.* **2012**, *4*, 43–45.
38. Arokiyaraj, S.; Vincent, S.; Saravanan, M.; Lee, Y.; Oh, Y.K.; Kim, K.H. Green Synthesis of Silver Nanoparticles Using *Rheum Palmatum* Root Extract and Their Antibacterial Activity against *Staphylococcus Aureus* and *Pseudomonas Aeruginosa*. *Artif. Cells Nanomed. Biotechnol.* **2017**, *45*, 372–379.
39. Sumathi, S.; Thomas, A. Eco-Friendly and Antibacterial Finishes of Organic Fabrics Using Herbal Composite Microencapsules. *Int. J. Pharma Bio Sci.* **2017**, *8*, 310–321.
40. Joseph, S.; Mathew, B. Microwave Assisted Biosynthesis of Silver Nanoparticles Using the Rhizome Extract of *Alpinia Galanga* and Evaluation of Their Catalytic and Antimicrobial Activities. *J. Nanopart.* **2014**, *2014*, 967802.
41. Ahmed, S.; Saifullah; Ahmad, M.; Swami, B.L.; Ikram, S. Green Synthesis of Silver Nanoparticles Using *Azadirachta Indica* Aqueous Leaf Extract. *J. Radiat. Res. Appl. Sci.* **2016**, *9*, 1–7. <https://doi.org/10.1016/j.jrras.2015.06.006>.
42. Dhand, V.; Soumya, L.; Bharadwaj, S.; Chakra, S.; Bhatt, D.; Sreedhar, B. Green Synthesis of Silver Nanoparticles Using *Coffea Arabica* Seed Extract and Its Antibacterial Activity. *Mater. Sci. Eng. C* **2016**, *58*, 36–43. <https://doi.org/10.1016/j.msec.2015.08.018>.
43. Fatimah, I.; Indriani, N. Silver Nanoparticles Synthesized Using *Lantana Camara* Flower Extract by Reflux, Microwave and Ultrasound Methods. *Chem. J. Mold.* **2018**, *13*, 95–102.
44. Kumar, B.; Smita, K.; Cumbal, L.; Debut, A. Green Synthesis of Silver Nanoparticles Using Andean Blackberry Fruit Extract. *Saudi J. Biol. Sci.* **2017**, *24*, 45–50.
45. Kumar, B.; Smita, K.; Cumbal, L.; Angulo, Y. Fabrication of Silver Nanoplates Using *Nephelium Lappaceum* (Rambutan) Peel: A Sustainable Approach. *J. Mol. Liq.* **2015**, *211*, 476–480.
46. Ojha, S.; Sett, A.; Bora, U. Green Synthesis of Silver Nanoparticles by *Ricinus Communis* Var. *Carmencita* Leaf Extract and Its Antibacterial Study. *Adv. Nat. Sci. Nanosci. Nanotechnol.* **2017**, *8*, 35009.
47. Joshi, P.S.; Ramesh, G.; Packiyam, J.E.; Jayanna, S.K. Green Synthesis and Evaluation of Silver Nanoparticles Using Leaf Extract from *Calotropis Gigantea*. *Int. J. Curr. Biotechnol.* **2007**, *5*, 1–5.
48. Ahmed, B.; Syed, A.; Ali, K.; Elgorban, A.M.; Khan, A.; Lee, J.; AL-Shwaiman, H.A. Synthesis of Gallotannin Capped Iron Oxide Nanoparticles and Their Broad Spectrum Biological Applications. *RSC Adv.* **2021**, *11*, 9880–9893. <https://doi.org/10.1039/d1ra00220a>.

49. Ali, K.; Saquib, Q.; Ahmed, B.; Siddiqui, M.A.; Ahmad, J.; Al-Shaeri, M.; Al-Khedhairi, A.A.; Musarrat, J. Bio-Functionalized CuO Nanoparticles Induced Apoptotic Activities in Human Breast Carcinoma Cells and Toxicity against *Aspergillus Flavus*: An in Vitro Approach. *Process Biochem.* **2020**, *91*, 387–397. <https://doi.org/10.1016/j.procbio.2020.01.008>.
50. Ahmed, B.; Solanki, B.; Zaidi, A.; Khan, M.S.; Musarrat, J. Bacterial Toxicity of Biomimetic Green Zinc Oxide Nanoantibiotic: Insights into ZnONP Uptake and Nanocolloid-Bacteria Interface. *Toxicol. Res.* **2019**, *8*, 246–261. <https://doi.org/10.1039/C8TX00267C>.
51. Ali, K.; Ahmed, B.; Khan, M.S.; Musarrat, J. Differential Surface Contact Killing of Pristine and Low EPS *Pseudomonas Aeruginosa* with Aloe Vera Capped Hematite ( $\alpha$ -Fe<sub>2</sub>O<sub>3</sub>) Nanoparticles. *J. Photochem. Photobiol. B Biol.* **2018**, *188*, 146–158. <https://doi.org/10.1016/j.jphotobiol.2018.09.017>.
52. Jebakumar Immanuel Edison, T.N.; Sethuraman, M.G. Electrocatalytic Reduction of Benzyl Chloride by Green Synthesized Silver Nanoparticles Using Pod Extract of *Acacia Nilotica*. *ACS Sustain. Chem. Eng.* **2013**, *1*, 1326–1332.
53. Mallikarjuna, K.; Narasimha, G.; Dillip, G.R.; Praveen, B.; Shreedhar, B.; Lakshmi, C.S.; Reddy, B.V.S.; Raju, B.D.P. Green Synthesis of Silver Nanoparticles Using Ocimum Leaf Extract and Their Characterization. *Dig. J. Nanomater. Biostruct.* **2011**, *6*, 181–186.
54. Vanaja, M.; Annadurai, G. *Coleus Aromaticus* Leaf Extract Mediated Synthesis of Silver Nanoparticles and Its Bactericidal Activity. *Appl. Nanosci.* **2013**, *3*, 217–223.
55. Ajitha, B.; Reddy, Y.A.K.; Reddy, P.S. Green Synthesis and Characterization of Silver Nanoparticles Using *Lantana Camara* Leaf Extract. *Mater. Sci. Eng. C* **2015**, *49*, 373–381.
56. Reddy, N.J.; Vali, D.N.; Rani, M.; Rani, S.S. Evaluation of Antioxidant, Antibacterial and Cytotoxic Effects of Green Synthesized Silver Nanoparticles by Piper Longum Fruit. *Mater. Sci. Eng. C* **2014**, *34*, 115–122.
57. Vasanth, K.; Ilango, K.; MohanKumar, R.; Agrawal, A.; Dubey, G.P. Anticancer Activity of *Moringa Oleifera* Mediated Silver Nanoparticles on Human Cervical Carcinoma Cells by Apoptosis Induction. *Colloids Surf. B Biointerfaces* **2014**, *117*, 354–359.
58. Atale, N.; Saxena, S.; Nirmala, J.G.; Narendhirakannan, R.T.; Mohanty, S.; Rani, V. Synthesis and Characterization of *Syzygium Cumini* Nanoparticles for Its Protective Potential in High Glucose-Induced Cardiac Stress: A Green Approach. *Appl. Biochem. Biotechnol.* **2017**, *181*, 1140–1154.
59. Anil Kumar, S.; Abyaneh, M.K.; Gosavi, S.W.; Kulkarni, S.K.; Pasricha, R.; Ahmad, A.; Khan, M.I. Nitrate Reductase-Mediated Synthesis of Silver Nanoparticles from AgNO<sub>3</sub>. *Biotechnol. Lett.* **2007**, *29*, 439–445.
60. Saratale, R.G.; Karuppusamy, I.; Saratale, G.D.; Pugazhendhi, A.; Kumar, G.; Park, Y.; Ghodake, G.S.; Bharagava, R.N.; Banu, J.R.; Shin, H.S. A Comprehensive Review on Green Nanomaterials Using Biological Systems: Recent Perception and Their Future Applications. *Colloids Surf. B Biointerfaces* **2018**, *170*, 20–35.
61. Malarkodi, C.; Rajeshkumar, S.; Paulkumar, K.; Gnanajobitha, G.; Vanaja, M.; Annadurai, G. Bacterial Synthesis of Silver Nanoparticles by Using Optimized Biomass Growth of *Bacillus* Sp. *Nanosci. Nanotechnol.* **2013**, *3*, 26–32.
62. Hallol, M. Studies on Bacterial Synthesis of Silver Nanoparticles Using Gamma Radiation and Their Activity against Some Pathogenic Microbes. 2013. [https://inis.iaea.org/collection/NCLCollectionStore/\\_Public/46/066/46066330.pdf](https://inis.iaea.org/collection/NCLCollectionStore/_Public/46/066/46066330.pdf) (accessed on 25 July 2022).
63. Das, V.L.; Thomas, R.; Varghese, R.T.; Soniya, E.V.; Mathew, J.; Radhakrishnan, E.K. Extracellular Synthesis of Silver Nanoparticles by the *Bacillus* Strain CS 11 Isolated from Industrialized Area. *3 Biotech* **2014**, *4*, 121–126.
64. Gandhi, H.; Khan, S. Biological Synthesis of Silver Nanoparticles and Its Antibacterial Activity. *J. Nanomed. Nanotechnol.* **2016**, *7*, 1000366.
65. Parikh, R.Y.; Ramanathan, R.; Coloe, P.J.; Bhargava, S.K.; Patole, M.S.; Shouche, Y.S.; Bansal, V. Genus-Wide Physicochemical Evidence of Extracellular Crystalline Silver Nanoparticles Biosynthesis by *Morganella* Spp. *PLoS ONE* **2011**, *6*, e21401.
66. Shivaji, S.; Madhu, S.; Singh, S. Extracellular Synthesis of Antibacterial Silver Nanoparticles Using Psychrophilic Bacteria. *Process Biochem.* **2011**, *46*, 1800–1807.
67. Saravanan, M.; Barik, S.K.; MubarakAli, D.; Prakash, P.; Pugazhendhi, A. Synthesis of Silver Nanoparticles from *Bacillus Brevis* (NCIM 2533) and Their Antibacterial Activity against Pathogenic Bacteria. *Microb. Pathog.* **2018**, *116*, 221–226. <https://doi.org/10.1016/j.micpath.2018.01.038>.
68. Mukherjee, A.; Sarkar, D.; Sasmal, S. A Review of Green Synthesis of Metal Nanoparticles Using Algae. *Front. Microbiol.* **2021**, *12*, 693899.
69. Akther, T.; Mathipi, V.; Kumar, N.S.; Davoodbasha, M.; Srinivasan, H. Fungal-Mediated Synthesis of Pharmaceutically Active Silver Nanoparticles and Anticancer Property against A549 Cells through Apoptosis. *Environ. Sci. Pollut. Res.* **2019**, *26*, 13649–13657.
70. Barabadi, H.; Tajani, B.; Moradi, M.; Damavandi Kamali, K.; Meena, R.; Honary, S.; Mahjoub, M.A.; Saravanan, M. *Penicillium* Family as Emerging Nanofactory for Biosynthesis of Green Nanomaterials: A Journey into the World of Microorganisms. *J. Clust. Sci.* **2019**, *30*, 843–856.
71. Gade, A.; Ingle, A.; Whiteley, C.; Rai, M. Mycogenic Metal Nanoparticles: Progress and Applications. *Biotechnol. Lett.* **2010**, *32*, 593–600.
72. Jena, J.; Pradhan, N.; Dash, B.P.; Sukla, L.B.; Panda, P.K. Biosynthesis and Characterization of Silver Nanoparticles Using Microalga *Chlorococcum Humicola* and Its Antibacterial Activity. *Int. J. Nanomater Biostruct* **2013**, *3*, 1–8.
73. Jena, J.; Pradhan, N.; Dash, B.P.; Panda, P.K.; Mishra, B.K. Pigment Mediated Biogenic Synthesis of Silver Nanoparticles Using *Diatom Amphora* Sp. and Its Antimicrobial Activity. *J. Saudi Chem. Soc.* **2015**, *19*, 661–666.
74. Kathiraven, T.; Sundaramanickam, A.; Shanmugam, N.; Balasubramanian, T. Green Synthesis of Silver Nanoparticles Using Marine Algae *Caulerpa Racemosa* and Their Antibacterial Activity against Some Human Pathogens. *Appl. Nanosci.* **2015**, *5*, 499–504.

75. Sahayaraj, K.; Rajesh, S.; Rath, J.M. Silver nanoparticles biosynthesis using marine alga *Padina pavonica* (Linn.) and its microbicidal activity. *Dig. J. Nanomater. Biostruct.* **2012**, *7*, 1557–1567.
76. Kannan, R.; Arumugam, R.; Ramya, D.; Manivannan, K.; Anantharaman, P. Green Synthesis of Silver Nanoparticles Using Marine Macroalga *Chaetomorpha Linum*. *Appl. Nanosci.* **2013**, *3*, 229–233.
77. Pugazhendhi, A.; Prabakar, D.; Jacob, J.M.; Karuppusamy, I.; Saratale, R.G. Synthesis and Characterization of Silver Nanoparticles Using *Gelidium Amansii* and Its Antimicrobial Property against Various Pathogenic Bacteria. *Microb. Pathog.* **2018**, *114*, 41–45.
78. Bhainsa, K.C.; D'souza, S.F. Extracellular Biosynthesis of Silver Nanoparticles Using the Fungus *Aspergillus Fumigatus*. *Colloids Surf. B Biointerfaces* **2006**, *47*, 160–164.
79. Kathiresan, K.; Manivannan, S.; Nabeel, M.A.; Dhivya, B. Studies on Silver Nanoparticles Synthesized by a Marine Fungus, *Penicillium Fellutanum* Isolated from Coastal Mangrove Sediment. *Colloids Surf. B Biointerfaces* **2009**, *71*, 133–137.
80. Vigneshwaran, N.; Ashtaputre, N.M.; Varadarajan, P.V.; Nachane, R.P.; Paralikar, K.M.; Balasubramanya, R.H. Biological Synthesis of Silver Nanoparticles Using the Fungus *Aspergillus Flavus*. *Mater. Lett.* **2007**, *61*, 1413–1418.
81. Basavaraja, S.; Balaji, S.D.; Lagashetty, A.; Rajasab, A.H.; Venkataraman, A. Extracellular Biosynthesis of Silver Nanoparticles Using the Fungus *Fusarium Semitectum*. *Mater. Res. Bull.* **2008**, *43*, 1164–1170.
82. Gajbhiye, M.; Kesharwani, J.; Ingle, A.; Gade, A.; Rai, M. Fungus-Mediated Synthesis of Silver Nanoparticles and Their Activity against Pathogenic Fungi in Combination with Fluconazole. *Nanomed. Nanotechnol. Biol. Med.* **2009**, *5*, 382–386. <https://doi.org/10.1016/j.nano.2009.06.005>.
83. Rashidipour, M.; Heydari, R. Biosynthesis of Silver Nanoparticles Using Extract of Olive Leaf: Synthesis and in Vitro Cytotoxic Effect on MCF-7 Cells. *J. Nanostruct. Chem.* **2014**, *4*, 1–6.
84. Majeed Khan, M.A.; Kumar, S.; Ahamed, M.; Alrokayan, S.A.; AlSalhi, M.S. Structural and Thermal Studies of Silver Nanoparticles and Electrical Transport Study of Their Thin Films. *Nanoscale Res. Lett.* **2011**, *6*, 1–8.
85. Njagi, E.C.; Huang, H.; Stafford, L.; Genuino, H.; Galindo, H.M.; Collins, J.B.; Hoag, G.E.; Suib, S.L. Biosynthesis of Iron and Silver Nanoparticles at Room Temperature Using Aqueous Sorghum Bran Extracts. *Langmuir* **2011**, *27*, 264–271.
86. Lukman, A.I.; Gong, B.; Marjo, C.E.; Roessner, U.; Harris, A.T. Facile Synthesis, Stabilization, and Anti-Bacterial Performance of Discrete Ag Nanoparticles Using Medicago Sativa Seed Exudates. *J. Colloid Interface Sci.* **2011**, *353*, 433–444.
87. Raju, D.; Mehta, U.J.; Hazra, S. Synthesis of Gold Nanoparticles by Various Leaf Fractions of *Semecarpus Anacardium* L. Tree. *Trees* **2011**, *25*, 145–151.
88. Marchiol, L. Synthesis of Metal Nanoparticles in Living Plants. *Ital. J. Agron.* **2012**, *7*, e37–e37.
89. Veerasamy, R.; Xin, T.Z.; Gunasagaran, S.; Xiang, T.F.W.; Yang, E.F.C.; Jeyakumar, N.; Dhanaraj, S.A. Biosynthesis of Silver Nanoparticles Using Mangosteen Leaf Extract and Evaluation of Their Antimicrobial Activities. *J. Saudi Chem. Soc.* **2011**, *15*, 113–120.
90. Krishnaraj, C.; Ramachandran, R.; Mohan, K.; Kalaichelvan, P.T. Optimization for Rapid Synthesis of Silver Nanoparticles and Its Effect on Phytopathogenic Fungi. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **2012**, *93*, 95–99. <https://doi.org/10.1016/j.saa.2012.03.002>.
91. Ali, M.; Ahmed, T.; Wu, W.; Hossain, A.; Hafeez, R.; Islam Masum, M.; Wang, Y.; An, Q.; Sun, G.; Li, B. Advancements in Plant and Microbe-Based Synthesis of Metallic Nanoparticles and Their Antimicrobial Activity against Plant Pathogens. *Nanomaterials* **2020**, *10*, 1146.
92. Mittal, A.K.; Chisti, Y.; Banerjee, U.C. Synthesis of Metallic Nanoparticles Using Plant Extracts. *Biotechnol. Adv.* **2013**, *31*, 346–356.
93. Iravani, S. Green Synthesis of Metal Nanoparticles Using Plants. *Green Chem.* **2011**, *13*, 2638–2650.
94. Sre, P.R.R.; Reka, M.; Poovazhagi, R.; Kumar, M.A.; Murugesan, K. Antibacterial and Cytotoxic Effect of Biologically Synthesized Silver Nanoparticles Using Aqueous Root Extract of *Erythrina Indica* Lam. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **2015**, *135*, 1137–1144.
95. Braithwaite, M.C.; Tyagi, C.; Tomar, L.K.; Kumar, P.; Choonara, Y.E.; Pillay, V. Nutraceutical-Based Therapeutics and Formulation Strategies Augmenting Their Efficiency to Complement Modern Medicine: An Overview. *J. Funct. Foods* **2014**, *6*, 82–99.
96. Bose, D.; Chatterjee, S. Biogenic Synthesis of Silver Nanoparticles Using Guava (*Psidium Guajava*) Leaf Extract and Its Antibacterial Activity against *Pseudomonas Aeruginosa*. *Appl. Nanosci.* **2016**, *6*, 895–901.
97. Rai, M.K.; Deshmukh, S.D.; Ingle, A.P.; Gade, A.K. Silver Nanoparticles: The Powerful Nanoweapon against Multidrug-resistant Bacteria. *J. Appl. Microbiol.* **2012**, *112*, 841–852.
98. Ahmed, B.; Ameen, F.; Rizvi, A.; Ali, K.; Sonbol, H.; Zaidi, A.; Khan, M.S.; Musarrat, J. Destruction of Cell Topography, Morphology, Membrane, Inhibition of Respiration, Biofilm Formation, and Bioactive Molecule Production by Nanoparticles of Ag, ZnO, CuO, TiO<sub>2</sub>, and Al<sub>2</sub>O<sub>3</sub> toward Beneficial Soil Bacteria. *ACS Omega* **2020**, *5*, 7861–7876. <https://doi.org/10.1021/acsomega.9b04084>.
99. Burduşel, A.-C.; Gherasim, O.; Grumezescu, A.M.; Mogoantă, L.; Ficai, A.; Andronescu, E. Biomedical Applications of Silver Nanoparticles: An up-to-Date Overview. *Nanomaterials* **2018**, *8*, 681.
100. Kaviya, S.; Santhanalakshmi, J.; Viswanathan, B.; Muthumary, J.; Srinivasan, K. Biosynthesis of Silver Nanoparticles Using Citrus Sinensis Peel Extract and Its Antibacterial Activity. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **2011**, *79*, 594–598.
101. Palanisamy, S.; Rajasekar, P.; Vijayaprasath, G.; Ravi, G.; Manikandan, R.; Prabhu, N.M. A Green Route to Synthesis Silver Nanoparticles Using *Sargassum Polycystum* and Its Antioxidant and Cytotoxic Effects: An in Vitro Analysis. *Mater. Lett.* **2017**, *189*, 196–200.

102. Da Rosa, C.G.; de Melo, A.P.Z.; Sganzerla, W.G.; Machado, M.H.; Nunes, M.R.; de Maciel, M.V.O.B.; Bertoldi, F.C.; Barreto, P.L.M. Application in Situ of Zein Nanocapsules Loaded with Origanum Vulgare Linneus and Thymus Vulgaris as a Preservative in Bread. *Food Hydrocoll.* **2020**, *99*, 105339.
103. Kang, Y.O.; Lee, T.S.; Park, W.H. Green Synthesis and Antimicrobial Activity of Silver Chloride Nanoparticles Stabilized with Chitosan Oligomer. *J. Mater. Sci. Mater. Med.* **2014**, *25*, 2629–2638.
104. Wang, Y.-W.; Tang, H.; Wu, D.; Liu, D.; Liu, Y.; Cao, A.; Wang, H. Enhanced Bactericidal Toxicity of Silver Nanoparticles by the Antibiotic Gentamicin. *Environ. Sci. Nano* **2016**, *3*, 788–798.
105. Wong, K.K.Y.; Liu, X. Silver Nanoparticles—The Real “Silver Bullet” in Clinical Medicine? *Medchemcomm* **2010**, *1*, 125–131.
106. Wu, J.; Yu, C.; Tan, Y.; Hou, Z.; Li, M.; Shao, F.; Lu, X. Effects of Prenatal Exposure to Silver Nanoparticles on Spatial Cognition and Hippocampal Neurodevelopment in Rats. *Environ. Res.* **2015**, *138*, 67–73.
107. Yuan, Z.; Li, J.; Cui, L.; Xu, B.; Zhang, H.; Yu, C.P. Interaction of Silver Nanoparticles with Pure Nitrifying Bacteria. *Chemosphere* **2013**, *90*, 1404–1411. <https://doi.org/10.1016/j.chemosphere.2012.08.032>.
108. Hajipour, M.J.; Fromm, K.M.; Ashkarran, A.A.; de Aberasturi, D.J.; de Larramendi, I.R.; Rojo, T.; Serpooshan, V.; Parak, W.J.; Mahmoudi, M. Antibacterial Properties of Nanoparticles. *Trends Biotechnol.* **2012**, *30*, 499–511.
109. Lemire, J.A.; Harrison, J.J.; Turner, R.J. Antimicrobial Activity of Metals: Mechanisms, Molecular Targets and Applications. *Nat. Rev. Microbiol.* **2013**, *11*, 371–384. <https://doi.org/10.1038/nrmicro3028>.
110. Alghuthaymi, M.A.; Almoammar, H.; Rai, M.; Said-Galiev, E.; Abd-El Salam, K.A. Myconanoparticles: Synthesis and Their Role in Phytopathogens Management. *Biotechnol. Biotechnol. Equip.* **2015**, *29*, 221–236.
111. Masum, M.; Islam, M.; Siddiq, M.; Ali, K.A.; Zhang, Y.; Abdallah, Y.; Ibrahim, E.; Qiu, W.; Yan, C.; Li, B. Biogenic Synthesis of Silver Nanoparticles Using Phyllanthus Emblica Fruit Extract and Its Inhibitory Action against the Pathogen Acidovorax Oryzae Strain RS-2 of Rice Bacterial Brown Stripe. *Front. Microbiol.* **2019**, *10*, 820.
112. Ibrahim, E.; Zhang, M.; Zhang, Y.; Hossain, A.; Qiu, W.; Chen, Y.; Wang, Y.; Wu, W.; Sun, G.; Li, B. Green-Synthesization of Silver Nanoparticles Using Endophytic Bacteria Isolated from Garlic and Its Antifungal Activity against Wheat Fusarium Head Blight Pathogen Fusarium Graminearum. *Nanomaterials* **2020**, *10*, 219.
113. Kędziora, A.; Speruda, M.; Krzyżewska, E.; Rybka, J.; Lukowiak, A.; Bugla-Płoskońska, G. Similarities and Differences between Silver Ions and Silver in Nanoforms as Antibacterial Agents. *Int. J. Mol. Sci.* **2018**, *19*, 444.
114. Yun'an Qing, L.C.; Li, R.; Liu, G.; Zhang, Y.; Tang, X.; Wang, J.; Liu, H.; Qin, Y. Potential Antibacterial Mechanism of Silver Nanoparticles and the Optimization of Orthopedic Implants by Advanced Modification Technologies. *Int. J. Nanomed.* **2018**, *13*, 3311.
115. Ibrahim, E.; Fouad, H.; Zhang, M.; Zhang, Y.; Qiu, W.; Yan, C.; Li, B.; Mo, J.; Chen, J. Biosynthesis of Silver Nanoparticles Using Endophytic Bacteria and Their Role in Inhibition of Rice Pathogenic Bacteria and Plant Growth Promotion. *RSC Adv.* **2019**, *9*, 29293–29299.
116. Singh, A.; Gautam, P.K.; Verma, A.; Singh, V.; Shivapriya, P.M.; Shivalkar, S.; Sahoo, A.K.; Samanta, S.K. Green Synthesis of Metallic Nanoparticles as Effective Alternatives to Treat Antibiotics Resistant Bacterial Infections: A Review. *Biotechnol. Rep.* **2020**, *25*, e00427.
117. Tortella, G.; Rubilar, O.; Fincheira, P.; Pieretti, J.C.; Duran, P.; Lourenço, I.M.; Seabra, A.B. Bactericidal and Virucidal Activities of Biogenic Metal-Based Nanoparticles: Advances and Perspectives. *Antibiotics* **2021**, *10*, 783.
118. Andleeb, S.; Tariq, F.; Muneer, A.; Nazir, T.; Shahid, B.; Latif, Z.; Abbasi, S.A.; ul Haq, I.; Majeed, Z.; Khan, S.U.-D. In Vitro Bactericidal, Antidiabetic, Cytotoxic, Anticoagulant, and Hemolytic Effect of Green-Synthesized Silver Nanoparticles Using Allium Sativum Clove Extract Incubated at Various Temperatures. *Green Process. Synth.* **2020**, *9*, 538–553.
119. Rodríguez-Serrano, C.; Guzmán-Moreno, J.; Ángeles-Chávez, C.; Rodríguez-González, V.; Ortega-Sigala, J.J.; Ramírez-Santoyo, R.M.; Vidales-Rodríguez, L.E. Biosynthesis of Silver Nanoparticles by Fusarium Scirpi and Its Potential as Antimicrobial Agent against Uropathogenic Escherichia Coli Biofilms. *PLoS ONE* **2020**, *15*, e0230275.
120. Noshad, A.; Iqbal, M.; Hetherington, C.; Wahab, H. Biogenic AgNPs—a Nano Weapon against Bacterial Canker of Tomato (Bct). *Adv. Agric.* **2020**, *2020*, 1–10.
121. Le Thi, H.; Nguyen, T.P.H.; Le Trong, D.; Vu, T.H.; Le Thi, V.; Hoang, T.G.; Chu, D.H.; Nguyen, T.H.; Nguyen, D.P.; Le Huy, H. Synthesis of Chitosan Stabilized Silver Nanoparticles and Evaluation of the in Vitro Antibacterial Activity Against Xanthomonas Oryzae P.V. Oryzae Causing Blight Disease of Rice. *VNU J. Sci. Nat. Sci. Technol.* **2021**, *6*, 65–75.
122. Cheng, H.-J.; Wang, H.; Zhang, J.-Z. Phytosynthesis of Silver Nanoparticles Using Three Flower Extracts and Their Antibacterial Activities against Pathogen Ralstonia Solanacearum Strain YY06 of Bacterial Wilt. *Front. Microbiol.* **2020**, *11*, 2110.
123. Xing, Y.; Liao, X.; Liu, X.; Li, W.; Huang, R.; Tang, J.; Xu, Q.; Li, X.; Yu, J. Characterization and Antimicrobial Activity of Silver Nanoparticles Synthesized with the Peel Extract of Mango. *Materials* **2021**, *14*, 5878.
124. Ahmed, T.; Shahid, M.; Noman, M.; Niazi, M.B.K.; Mahmood, F.; Manzoor, I.; Zhang, Y.; Li, B.; Yang, Y.; Yan, C. Silver Nanoparticles Synthesized by Using Bacillus Cereus SZT1 Ameliorated the Damage of Bacterial Leaf Blight Pathogen in Rice. *Pathogens* **2020**, *9*, 160.
125. del Carmen Travieso Novelles, M.; Ortega, A.R.; Pita, B.A.; López, M.C.; Pérez, L.D.; Medina, E.A.; Pérez, O.P. Biosynthesis of Fluorescent Silver Nanoparticles from Leea Coccinea Leaves and Their Antibacterial Potentialities against Xanthomonas Phaseoli P.V. Phaseoli. *Bioresour. Bioprocess.* **2021**, *8*, 1–11.
126. Mazzon, M.; Marsh, M. Targeting Viral Entry as a Strategy for Broad-Spectrum Antivirals. *F1000Research* **2019**, *8*, 1–10.
127. Galdiero, S.; Falanga, A.; Vitiello, M.; Cantisani, M.; Marra, V.; Galdiero, M. Silver Nanoparticles as Potential Antiviral Agents. *Molecules* **2011**, *16*, 8894–8918.

128. Noha, K.; Bondok, A.M.; El-DougDoug, K.A. Evaluation of Silver Nanoparticles as Antiviral Agent against ToMV and PVY in Tomato Plants. *Sciences* **2018**, *8*, 100–111.
129. Elbeshehy, E.K.F.; Elazzazy, A.M.; Aggelis, G. Silver Nanoparticles Synthesis Mediated by New Isolates of *Bacillus* Spp., Nanoparticle Characterization and Their Activity against Bean Yellow Mosaic Virus and Human Pathogens. *Front. Microbiol.* **2015**, *6*, 453.
130. Shafie, R.M.; Salama, A.M.; Farroh, K.Y. Silver Nanoparticles Activity against Tomato Spotted Wilt Virus. *Middle East J. Appl. Sci.* **2018**, *7*, 1251–1267.
131. El-Shazly, M.A.; Attia, Y.A.; Kabil, F.F.; Anis, E.; Hazman, M. Inhibitory Effects of Salicylic Acid and Silver Nanoparticles on Potato Virus Y-Infected Potato Plants in Egypt. *Middle East J. Agric. Res.* **2017**, *6*, 835–848.
132. Jain, D.; Kothari, S.L. Green Synthesis of Silver Nanoparticles and Their Application in Plant Virus Inhibition. *J. Mycol Plant Pathol* **2014**, *44*, 21–24.
133. Mahfouze, H.A.; El-DougDoug, N.K.; Mahfouze, S.A. Virucidal Activity of Silver Nanoparticles against Banana Bunchy Top Virus (BBTV) in Banana Plants. *Bull. Natl. Res. Cent.* **2020**, *44*, 1–11.
134. Cai, L.; Cai, L.; Jia, H.; Liu, C.; Wang, D.; Sun, X. Foliar Exposure of Fe<sub>3</sub>O<sub>4</sub> Nanoparticles on *Nicotiana Benthamiana*: Evidence for Nanoparticles Uptake, Plant Growth Promoter and Defense Response Elicitor against Plant Virus. *J. Hazard. Mater.* **2020**, *393*, 122415. <https://doi.org/10.1016/j.jhazmat.2020.122415>.
135. Vinković, T.; Novák, O.; Strnad, M.; Goessler, W.; Jurašin, D.D.; Parađiković, N.; Vrček, I.V. Cytokinin Response in Pepper Plants (*Capsicum Annuum* L.) Exposed to Silver Nanoparticles. *Environ. Res.* **2017**, *156*, 10–18.
136. Tripathi, D.K.; Tripathi, A.; Shweta; Singh, S.; Singh, Y.; Vishwakarma, K.; Yadav, G.; Sharma, S.; Singh, V.K.; Mishra, R.K.; Upadhyay, R.G.; et al. Uptake, Accumulation and Toxicity of Silver Nanoparticle in Autotrophic Plants, and Heterotrophic Microbes: A Concentric Review. *Front. Microbiol.* **2017**, *8*, 7.
137. Hassan, S.A.M.; Mahfouze, H.A.; Mahfouze, S.A.; Abd-Allatif, A.M. Genotoxicity Assessment of Nano-Particles on Micropropagated Olive (*Olea Europaea* L.) Plants Using RAPD and DAMD Markers. *Plant Arch* **2019**, *19*, 1985–1994.
138. Elazzazy, A.M.; Elbeshehy, E.K.F.; Betiha, M.A. In Vitro Assessment of Activity of Graphene Silver Composite Sheets against Multidrug-Resistant Bacteria and Tomato Bushy Stunt Virus. *Trop. J. Pharm. Res.* **2017**, *16*, 2705–2711.
139. Wang, Y.; Sun, C.; Xu, C.; Wang, Z.; Zhao, M.; Wang, C.; Liu, L.; Chen, F. Preliminary Experiments on Nano-Silver against Tobacco Mosaic Virus and Its Mechanism. *Tob. Sci. Technol* **2016**, *49*, 22–30.
140. Jo, Y.-K.; Cromwell, W.; Jeong, H.-K.; Thorkelson, J.; Roh, J.-H.; Shin, D.-B. Use of Silver Nanoparticles for Managing Gibberella Fujikuroi on Rice Seedlings. *Crop Prot.* **2015**, *74*, 65–69.
141. Nyilasi, I.; Kocsubé, S.; Krizsán, K.; Galgóczy, L.; Pesti, M.; Papp, T.; Vágvolgyi, C. In Vitro Synergistic Interactions of the Effects of Various Statins and Azoles against Some Clinically Important Fungi. *FEMS Microbiol. Lett.* **2010**, *307*, 175–184.
142. Guilger, M.; Pasquoto-Stigliani, T.; Bilesky-Jose, N.; Grillo, R.; Abhilash, P.C.; Fraceto, L.F.; Lima, R. de Biogenic Silver Nanoparticles Based on *Trichoderma Harzianum*: Synthesis, Characterization, Toxicity Evaluation and Biological Activity. *Sci. Rep.* **2017**, *7*, 1–13.
143. Auyeung, A.; Casillas-Santana, M.A.; Martínez-Castañón, G.A.; Slavin, Y.N.; Zhao, W.; Asnis, J.; Häfeli, U.O.; Bach, H. Effective Control of Molds Using a Combination of Nanoparticles. *PLoS ONE* **2017**, *12*, e0169940.
144. Fatima, F.; Verma, S.R.; Pathak, N.; Bajpai, P. Extracellular Mycosynthesis of Silver Nanoparticles and Their Microbicidal Activity. *J. Glob. Antimicrob. Resist.* **2016**, *7*, 88–92.
145. Mallmann, E.J.J.; Cunha, F.A.; Castro, B.N.M.F.; Maciel, A.M.; Menezes, E.A.; Fachine, P.B.A. Antifungal Activity of Silver Nanoparticles Obtained by Green Synthesis. *Rev. Inst. Med. Trop. Sao Paulo* **2015**, *57*, 165–167.
146. Gopinath, V.; Velusamy, P. Extracellular Biosynthesis of Silver Nanoparticles Using *Bacillus* Sp. GP-23 and Evaluation of Their Antifungal Activity towards *Fusarium Oxysporum*. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **2013**, *106*, 170–174.
147. Hahn, M. The Rising Threat of Fungicide Resistance in Plant Pathogenic Fungi: Botrytis as a Case Study. *J. Chem. Biol.* **2014**, *7*, 133–141.
148. Matsumura, Y.; Yoshikata, K.; Kunisaki, S.; Tsuchido, T. Mode of Bactericidal Action of Silver Zeolite and Its Comparison with That of Silver Nitrate. *Appl. Environ. Microbiol.* **2003**, *69*, 4278–4281.
149. Feng, Q.L.; Wu, J.; Chen, G.Q.; Cui, F.Z.; Kim, T.N.; Kim, J.O. A Mechanistic Study of the Antibacterial Effect of Silver Ions on *Escherichia Coli* and *Staphylococcus Aureus*. *J. Biomed. Mater. Res.* **2000**, *52*, 662–668. [https://doi.org/10.1002/1097-4636\(20001215\)52:4<662::AID-JBM10>3.0.CO;2-3](https://doi.org/10.1002/1097-4636(20001215)52:4<662::AID-JBM10>3.0.CO;2-3).
150. Rai, M.; Kon, K.; Ingle, A.; Duran, N.; Galdiero, S.; Galdiero, M. Broad-Spectrum Bioactivities of Silver Nanoparticles: The Emerging Trends and Future Prospects. *Appl. Microbiol. Biotechnol.* **2014**, *98*, 1951–1961.
151. Al-Thabaiti, S.A.; Khan, Z.; Manzoor, N. Biosynthesis of Silver Nanoparticles and Its Antibacterial and Antifungal Activities towards Gram-Positive, Gram-Negative Bacterial Strains and Different Species of *Candida* Fungus. *Bioprocess Biosyst. Eng.* **2015**, *38*, 1773–1781.
152. Pereira, L.; Dias, N.; Carvalho, J.; Fernandes, S.; Santos, C.; Lima, N. Synthesis, Characterization and Antifungal Activity of Chemically and Fungal-produced Silver Nanoparticles against *T. Richophyton Rubrum*. *J. Appl. Microbiol.* **2014**, *117*, 1601–1613.
153. Xia, Z.-K.; Ma, Q.-H.; Li, S.-Y.; Zhang, D.-Q.; Cong, L.; Tian, Y.-L.; Yang, R.-Y. The Antifungal Effect of Silver Nanoparticles on *Trichosporon Asahii*. *J. Microbiol. Immunol. Infect.* **2016**, *49*, 182–188.
154. Bera, R.K.; Mandal, S.M.; Raj, C.R. Antimicrobial Activity of Fluorescent Ag Nanoparticles. *Lett. Appl. Microbiol.* **2014**, *58*, 520–526.
155. Balakumaran, M.D.; Ramachandran, R.; Kalaichelvan, P.T. Exploitation of Endophytic Fungus, *Guignardia Mangiferae* for Extracellular Synthesis of Silver Nanoparticles and Their in Vitro Biological Activities. *Microbiol. Res.* **2015**, *178*, 9–17.

156. Ma, J.F.; Hiradate, S. Form of Aluminium for Uptake and Translocation in Buckwheat (*Fagopyrum Esculentum* Moench). *Planta* **2000**, *211*, 355–360.
157. Kim, S.W.; Jung, J.H.; Lamsal, K.; Kim, Y.S.; Min, J.S.; Lee, Y.S. Antifungal Effects of Silver Nanoparticles (AgNPs) against Various Plant Pathogenic Fungi. *Mycobiology* **2012**, *40*, 53–58. <https://doi.org/10.5941/MYCO.2012.40.1.053>.
158. Soenen, S.J.; Rivera-Gil, P.; Montenegro, J.-M.; Parak, W.J.; De Smedt, S.C.; Braeckmans, K. Cellular Toxicity of Inorganic Nanoparticles: Common Aspects and Guidelines for Improved Nanotoxicity Evaluation. *Nano Today* **2011**, *6*, 446–465.
159. Al-Otibi, F.; Perveen, K.; Al-Saif, N.A.; Alharbi, R.I.; Bokhari, N.A.; Albasher, G.; Al-Otaibi, R.M.; Al-Mosa, M.A. Biosynthesis of Silver Nanoparticles Using *Malva Parviflora* and Their Antifungal Activity. *Saudi J. Biol. Sci.* **2021**, *28*, 2229–2235.
160. Yassin, M.A.; Elgorban, A.M.; El-Samawaty, A.E.-R.M.A.; Almunqedhi, B.M.A. Biosynthesis of Silver Nanoparticles Using Penicillium Verrucosum and Analysis of Their Antifungal Activity. *Saudi J. Biol. Sci.* **2021**, *28*, 2123–2127.
161. Nguyen, D.H.; Vo, T.N.N.; Le, N.T.T.; Thi, D.P.N.; Thi, T.T.H. Evaluation of Saponin-Rich/Poor Leaf Extract-Mediated Silver Nanoparticles and Their Antifungal Capacity. *Green Process. Synth.* **2020**, *9*, 429–439.
162. Shafea, T.M.M.; Mahmoud, K.M. Green Synthesis, Characterization and Antimicrobial Activity of Silver Nanoparticles Using Locally Growing *Allium Sativum* Extract. *Zanco J. Pure Appl. Sci.* **2021**, *33*, 35–41.
163. Anum, F.; Jabeen, K.; Javad, S.; Iqbal, S.; Tahir, A.; Javed, Z.; Cruz-Martins, N.; Ayatollahi, S.A.; Sharifi-Rad, J.; Alshehri, M.M. Green Synthesized Silver Nanoparticles as Potent Antifungal Agent against *Aspergillus Terreus* Thom. *J. Nanomater.* **2021**, *2021*, 1–10.
164. Le, N.T.T.; Nguyen, D.H.; Nguyen, N.H.; Ching, Y.C.; Pham Nguyen, D.Y.; Ngo, C.Q.; Nhat, H.N.T.; Hoang Thi, T.T. Silver Nanoparticles Ecofriendly Synthesized by *Achyranthes Aspera* and *Scoparia Dulcis* Leaf Broth as an Effective Fungicide. *Appl. Sci.* **2020**, *10*, 2505.
165. Ghojavand, S.; Madani, M.; Karimi, J. Green Synthesis, Characterization and Antifungal Activity of Silver Nanoparticles Using Stems and Flowers of Feltly Germander. *J. Inorg. Organomet. Polym. Mater.* **2020**, *30*, 2987–2997.
166. Bocate, K.P.; Reis, G.F.; de Souza, P.C.; Junior, A.G.O.; Durán, N.; Nakazato, G.; Furlaneto, M.C.; de Almeida, R.S.; Panagio, L.A. Antifungal Activity of Silver Nanoparticles and Simvastatin against Toxigenic Species of *Aspergillus*. *Int. J. Food Microbiol.* **2019**, *291*, 79–86.
167. Nokkrut, B.; Pisuttipiched, S.; Khantayanuwong, S.; Puangsins, B. Silver Nanoparticle-Based Paper Packaging to Combat Black Anther Disease in Orchid Flowers. *Coatings* **2019**, *9*, 40.
168. Nguyen, D.H.; Vo, T.N.N.; Nguyen, N.T.; Ching, Y.C.; Hoang Thi, T.T. Comparison of Biogenic Silver Nanoparticles Formed by *Momordica Charantia* and *Psidium Guajava* Leaf Extract and Antifungal Evaluation. *PLoS ONE* **2020**, *15*, e0239360.
169. Mansoor, S.; Zahoor, I.; Baba, T.R.; Padder, S.A.; Bhat, Z.A.; Koul, A.M.; Jiang, L. Fabrication of Silver Nanoparticles against Fungal Pathogens. *Front. Nanotechnol.* **2021**, *3*, 679358. <https://doi.org/10.3389/fnano>.
170. Vrandečić, K.; Ćosić, J.; Ilić, J.; Ravnjak, B.; Selmani, A.; Galić, E.; Pem, B.; Barbir, R.; Vinković Vrček, I.; Vinković, T. Antifungal Activities of Silver and Selenium Nanoparticles Stabilized with Different Surface Coating Agents. *Pest Manag. Sci.* **2020**, *76*, 2021–2029.
171. Nicol, J.M.; Turner, S.J.; Coyne, D.L.; den Nijs, L.; Hockland, S.; Maafi, Z.T. Current Nematode Threats to World Agriculture. In *Genomics and Molecular Genetics of Plant-Nematode Interactions*; Springer: Berlin, Germany, 2011; pp. 21–43.
172. Baronia, R.; Kumar, P.; Singh, S.P.; Walia, R.K. Silver Nanoparticles as a Potential Nematicide against *Meloidogyne Graminicola*. *J. Nematol.* **2020**, *52*, 1–9.
173. Fouda, M.M.G.; Abdelsalam, N.R.; Gohar, I.M.A.; Hanfy, A.E.M.; Othman, S.I.; Zaitoun, A.F.; Allam, A.A.; Morsy, O.M.; El-Naggar, M. Utilization of High Throughput Microcrystalline Cellulose Decorated Silver Nanoparticles as an Eco-Nematicide on Root-Knot Nematodes. *Colloids Surf. B Biointerfaces* **2020**, *188*, 110805.
174. Lim, D.; Roh, J.; Eom, H.; Choi, J.; Hyun, J.; Choi, J. Oxidative Stress-related PMK-1 P38 MAPK Activation as a Mechanism for Toxicity of Silver Nanoparticles to Reproduction in the Nematode *Caenorhabditis Elegans*. *Environ. Toxicol. Chem.* **2012**, *31*, 585–592.
175. Miura, N.; Shinohara, Y. Cytotoxic Effect and Apoptosis Induction by Silver Nanoparticles in HeLa Cells. *Biochem. Biophys. Res. Commun.* **2009**, *390*, 733–737.
176. Hassan, M.E.M.; Zawam, H.S.; El-Nahas, S.E.M.; Desoukey, A.F. Comparison Study between Silver Nanoparticles and Two Nematicides against *Meloidogyne Incognita* on Tomato Seedlings. *Plant Pathol. J.* **2016**, *15*, 144–151.
177. Soliman, B.S.; Abbassy, M.A.; Abdel-Rasoul, M.A.; Nassar, A.M. Efficacy of Silver Nanoparticles of Extractives of *Artemisia Judaica* against Root-Knot Nematode. *J. Environ. Stud. Res* **2017**, *7*, 1–13.
178. Nassar, A.M.K. Effectiveness of Silver Nano-Particles of Extracts of *Urtica Urens* (*Urticaceae*) against Root-Knot Nematode *Meloidogyne Incognita*. *Asian J. Nematol.* **2016**, *5*, 14–19.
179. Walters, D.R.; Newton, A.C.; Lyon, G.D. *Induced Resistance for Plant Defense: A Sustainable Approach to Crop Protection*; John Wiley & Sons: New York, NY, USA, 2014; ISBN 1118371836.
180. Wuyts, N.; De Waele, D.; Swennen, R. Extraction and Partial Characterization of Polyphenol Oxidase from Banana (*Musa Acuminata* Grande Naine) Roots. *Plant Physiol. Biochem.* **2006**, *44*, 308–314.
181. Fabiyi, O.; Olatunji, G.; Atolani, O.; Olawuyi, O. Preparation of Bio-Nematicidal Nanoparticles of *Eucalyptus Officinalis* for the Control of Cyst Nematode (*Heterodera Sacchari*). *J. Anim. Plant. Sci.* **2020**, *30*, 1172–1177.
182. Kalaiselvi, D.; Mohankumar, A.; Shanmugam, G.; Nivitha, S.; Sundararaj, P. Green Synthesis of Silver Nanoparticles Using Latex Extract of *Euphorbia Tirucalli*: A Novel Approach for the Management of Root Knot Nematode, *Meloidogyne Incognita*. *Crop Prot.* **2019**, *117*, 108–114.

183. Abbassy, M.A.; Abdel-Rasoul, M.A.; Nassar, A.M.K.; Soliman, B.S.M. Nematicidal Activity of Silver Nanoparticles of Botanical Products against Root-Knot Nematode, *Meloidogyne Incognita*. *Arch. Phytopathol. Plant Prot.* **2017**, *50*, 909–926.
184. El-Deen, A.H.N.; El-Deeb, B.A. Effectiveness of Silver Nanoparticles against Root-Knot Nematode, *Meloidogyne Incognita* Infecting Tomato under Greenhouse Conditions. *J. Agric. Sci.* **2018**, *10*, 148–156.
185. Hamed, S.M.; Hagag, E.S.; El-Raouf, N.A. Green Production of Silver Nanoparticles, Evaluation of Their Nematicidal Activity against *Meloidogyne Javanica* and Their Impact on Growth of Faba Bean. *Beni-Suef Univ. J. Basic Appl. Sci.* **2019**, *8*, 1–12.
186. Abdellatif, K.F.; Abdelfattah, R.H.; El-Ansary, M.S.M. Green Nanoparticles Engineering on Root-Knot Nematode Infecting Egg-plants and Their Effect on Plant DNA Modification. *Iran. J. Biotechnol.* **2016**, *14*, 250.
187. Cromwell, W.A.; Yang, J.; Starr, J.L.; Jo, Y.-K. Nematicidal Effects of Silver Nanoparticles on Root-Knot Nematode in Bermudagrass. *J. Nematol.* **2014**, *46*, 261.
188. Ghareeb, R.Y.; EL-Saedy, M.A.M.; Fathy, M.M.; Hafez, E.E.; Basyony, A.B.A. Green Biosynthesized Silver Nanoparticles Using Macroalgae and Their Usage as a Bioagent on *Meloidogyne incognita*. *Plant Archives.* **2020**, *20*, 9682–9692.
189. Ardakani, A.S. Toxicity of Silver, Titanium and Silicon Nanoparticles on the Root-Knot Nematode, *Meloidogyne Incognita*, and Growth Parameters of Tomato. *Nematology* **2013**, *15*, 671–677.
190. El-Batal, A.I.; Attia, M.S.; Nofel, M.M.; El-Sayyad, G.S. Potential Nematicidal Properties of Silver Boron Nanoparticles: Synthesis, Characterization, in Vitro and in Vivo Root-Knot Nematode (*Meloidogyne Incognita*) Treatments. *J. Clust. Sci.* **2019**, *30*, 687–705.
191. Ghareeb, R.Y.; Alfay, H.; Fahmy, A.A.; Ali, H.M.; Abdelsalam, N.R. Utilization of *Cladophora Glomerata* Extract Nanoparticles as Eco-Nematicide and Enhancing the Defense Responses of Tomato Plants Infected by *Meloidogyne Javanica*. *Sci. Rep.* **2020**, *10*, 1–15.
192. Mikhailova, E.O. Silver Nanoparticles: Mechanism of Action and Probable Bio-Application. *J. Funct. Biomater.* **2020**, *11*, 84.
193. Jian, Y.; Chen, X.; Ahmed, T.; Shang, Q.; Zhang, S.; Ma, Z.; Yin, Y. Toxicity and Action Mechanisms of Silver Nanoparticles against the Mycotoxin-Producing Fungus *Fusarium Graminearum*. *J. Adv. Res.* **2022**, *38*, 1–12.
194. Ahmad, S.A.; Das, S.S.; Khatoon, A.; Ansari, M.T.; Afzal, M.; Hasnain, M.S.; Nayak, A.K. Bactericidal Activity of Silver Nanoparticles: A Mechanistic Review. *Mater. Sci. Energy Technol.* **2020**, *3*, 756–769.
195. Zhang, L.; Wu, L.; Si, Y.; Shu, K. Size-Dependent Cytotoxicity of Silver Nanoparticles to *Azotobacter Vinelandii*: Growth Inhibition, Cell Injury, Oxidative Stress and Internalization. *PLoS ONE* **2018**, *13*, e0209020. <https://doi.org/10.1371/journal.pone.0209020>.
196. Karn, B.; Kuiken, T.; Otto, M. Nanotechnology and in situ remediation: A review of the benefits and potential risks. *Ciência Saúde Coletiva* **2011**, *16*, 165–178.
197. Bergeson, L.L. Nanosilver: US EPA's pesticide office considers how best to proceed. *Environ. Qual. Manag.* **2010**, *19*, 79–85.
198. Gurav, A.S.; Kodas, T.T.; Wang, L.-M.; Kauppinen, E.I.; Joutsensaari, J. Generation of nanometer-size fullerene particles via vapor condensation. *Chem. Phys. Lett.* **1994**, *218*, 304–308.
199. Ahmed, B.; Rizvi, A.; Ali, K.; Lee, J.; Zaidi, A.; Khan, M.S.; Musarrat, J. Nanoparticles in the Soil-Plant System: A Review. *Environ. Chem. Lett.* **2021**, *19*, 1545–1609.
200. Morales-Díaz, A.B.; Ortega-Ortíz, H.; Juárez-Maldonado, A.; Cadenas-Pliego, G.; González-Morales, S.; Benavides-Mendoza, A. Application of Nanoelements in Plant Nutrition and Its Impact in Ecosystems. *Adv. Nat. Sci. Nanosci. Nanotechnol.* **2017**, *8*, 13001.