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Review

Agro-Nanotechnology as an Emerging Field: A Novel Sustainable Approach for Improving Plant Growth by Reducing Biotic Stress

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Abstract: In the present era, the global need for food is increasing rapidly; nanomaterials are a useful tool for improving crop production and yield. The application of nanomaterials can improve plant growth parameters. Biotic stress is induced by many microbes in crops and causes disease and high yield loss. Every year, approximately 20–40% of crop yield is lost due to plant diseases caused by various pests and pathogens. Current plant disease or biotic stress management mainly relies on toxic fungicides and pesticides that are potentially harmful to the environment. Nanotechnology emerged as an alternative for the sustainable and eco-friendly management of biotic stress induced by pests and pathogens on crops. In this review article, we assess the role and impact of different nanoparticles in plant disease management, and this review explores the direction in which nanoparticles can be utilized for improving plant growth and crop yield.

Keywords: plant diseases; nanoparticles; diseases; biotic stress; management; silver nanoparticles; zinc nanoparticles

1. Introduction

Crop cultivators suffer from high yield loss caused by various diseases. Biotic stress induced by microbes on crop plants reduces the crop yield and decreases the quality. Biotic stress causes disease in crops, which leads to the suffering of the plant. Diseases of the plant need to be controlled to maintain the abundance of food produced by farmers around the world. The management of crop diseases is very necessary to fulfill the food demand. Potato blight disease caused by plant pathogenic fungus *Phytopthora* caused more than one million deaths in Ireland [1]. Around 20–40% of agricultural crop yield losses occur globally due to various diseases caused by phytopathogenic bacteria, phytopathogenic fungi, pests, and weeds [2].

It is estimated that in 2050 the world's human population will reach around 10 billion, and around 800 million people in the world will be hungry and around 653 million people in the world will be undernourished in 2030, thus fulfilling the food demand will remain a huge challenge. The current research progress and disease management strategies are not enough to fulfill the food demand by 2050 [3]. The first green revolution made a huge difference in yield and food production, but in the last few years' crop production has been stagnant and food demand is increasing sharply, so now we need a second green revolution to fulfill the food demand of the population.

Different approaches are used by farmers to mitigate the impact of plant diseases. The agriculture system mainly relies on chemicals to manage crop diseases and inhibit the growth of phytopathogens, which cause diseases before and after crop harvesting. The excessive use of chemical pesticides, herbicides, and fungicides that are mainly used to control plant diseases causes harmful environmental and human health consequences. Tilman et al. [4] observed that the high use of chemical pesticides increases resistance in pathogens and pests, reduces nitrogen fixation, and the bioaccumulation of toxic pesticides occurs.

An example is the synthetic chemical pesticide DDT, dichlorodiphenyltrichloroethane, which was extensively used in agriculture for controlling plant pathogens and was found to be genotoxic in humans, causing endocrine disorders [5]. Water and soil pollution is also caused by the excessive use and misuse of these chemicals. There is an increasing demand day by day to reduce the use of synthetic chemicals. Consequently, the harmful effects of chemicals on wildlife, the environment, and human health have increased the need for alternative measures in the control of plant pathogens, so that some phytopathologists have focused their research on developing a new alternative that should replace the use of chemicals in controlling plant diseases.

Nanotechnology has revolutionized agriculture and can control plant diseases, although the field of nanotechnology is still in the nascent stage and needs more research analysis [6].The use of nanomaterials in agriculture will reduce the excessive use of toxic chemicals used for plant disease management (Figures 1 and 2).

"Nano" denotes one-billionth part, thus nanotechnology deals with small things. The word nano is used for materials with a size range of 0.1 to 100 nanometers [7,8]. The first time the term nanotechnology was used was by Taniguchi in 1974 to the science that largely deals with particles of nano size (1.0×10^{-9} m). When a bulk material is reduced to nano size, it has a high surface-to-volume ratio that may increase its reactivity and express some new properties [7,9]. The control of plant diseases and improving plant growth by the use of nanomaterials are some of the possible key applications in the area of plant pathology. Approximately 260,000–309,000 metric tons of nanoparticles were produced in 2010 globally, and the worldwide consumption of nanomaterials was approximately from 225,060 metric tons to 585,000 metric tons in 2014 to 2019 [10,11].

In this review article, recent research progress and the application of various nanoparticles for the sustainable management of the biotic stress of crop systems and impact on plant growth have been discussed. We try to cover the various problems associated with crop cultivation and plant diseases and the use of different nanomaterials to control phytopathogens and improve plant growth.

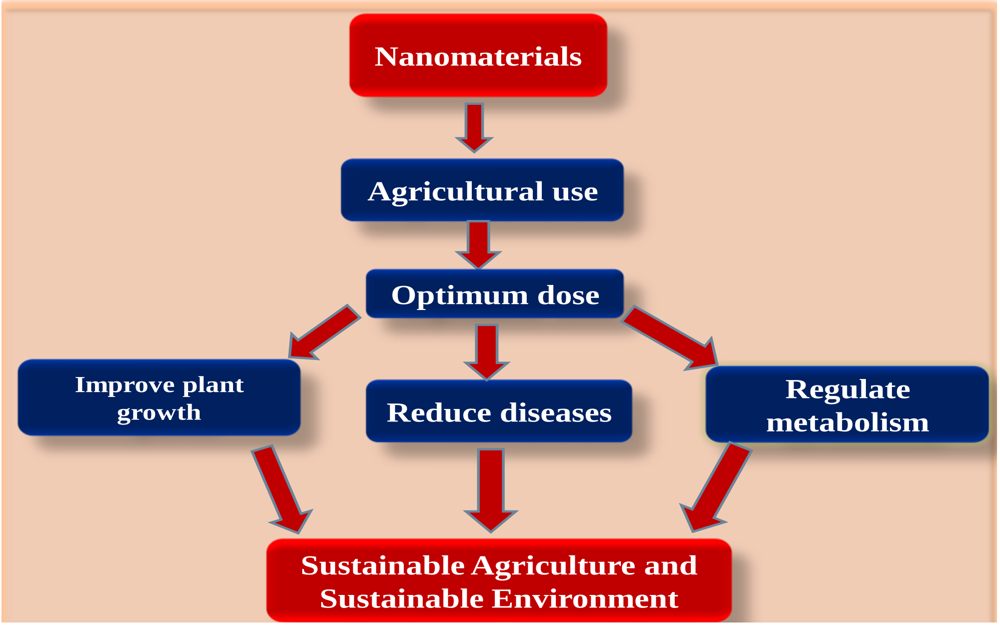

Figure 1. Schematic presentation of nanomaterials in agriculture [12].

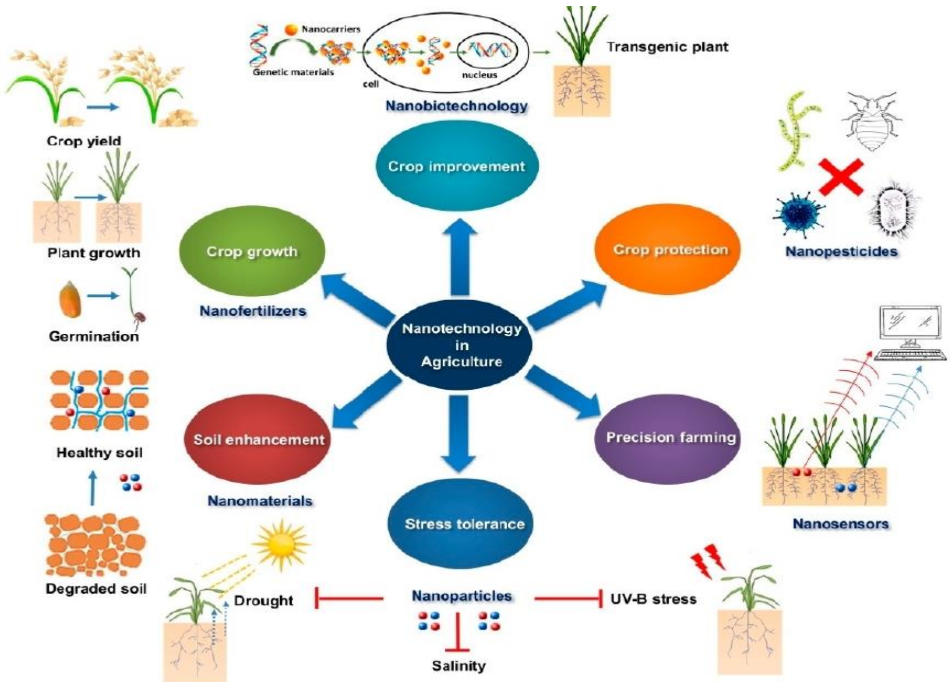

Figure 2. Various applications of nanotechnology in agriculture taken from [12].

2. Nanomaterials in Improving Plant Growth and Yield

Currently, around 1300 nanomaterials, with widespread potential applications, are available [13,14]. Nanoparticles can penetrate the cell wall because the cell wall is porous to 3.5–20 nm macromolecules. Nanoparticles can enter through stomatal openings. When stomata are present at the lower surface of leaves, the entry of nanoparticles (NPs) becomes difficult [15]. It is reported that nanoparticles of size $\leq$43 nm can penetrate and enter into stomata [16,17].

The effect of nanoparticles on crop plants is concentration-based. Many plant processes such as seed germination and plant growth are affected by NP concentration [18]. Many NPs have been reported to be beneficial for plant growth. Mahmoud et al. [19] used

Zn, B, Si, zeolite NPs on a potato plant and found that these nanoparticles have a positive effect on potato plants and they improve the plant growth. Khan and Siddiqui [20] treated eggplant with ZnONPs and found a foliar spray of ZnONPs causes the highest improvement in eggplant growth. Awasthi et al. [21] reported that ZnONPs have a positive effect on seed germination in the *Triticum aestivum* plant. Zinc oxide nanoparticles (ZnONPs) can enhance plant biomass and agriculture production [22]. Sabir et al. [23] also showed that nanocalcite ($CaCO_3$) application with Fe_2O_3, nano SiO_2, and MgO improved the uptake of Mg, Ca, and Fe, and also notably enhanced the intake of P with micronutrients Zn and Mn. Venkatachalam et al. [24] found that ZnONPs increase in photosynthetic pigment in the *Leucaena leucocephala* plant. Narendhran et al. [25] reported high chlorophyll-a', chlorophyll-'b' and total chlorophyll content in the *Sesamum indicum* plant when treated with ZnO NPs. Taheri et al. [26] observed that treatment of ZnONPs increases the increase in shoot dry matter in *Zea mays*. Tarafdar et al. [27] found that ZnONPs enhanced shoot and grain yield in the *Pennisetum glaucum* plant.

The application of titanium dioxide (TiO_2) on crops promotes plant growth parameters and can enhance the photosynthetic rate. Siddiqui et al. [28] usedTiO_2 and ZnONPs on beet root plants. They found that both NPs increased chlorophyll and carotenoid content, improved plant growth, and also improved super oxide dismutase (SOD), catalase (CAT), H_2O_2, and proline content in plants. ZnONPs were found to be better than TiO_2NPs on beetroot plants. Raliya et al. [29] reported that TiO_2NPs treatment improved shoots in the *Vigna radiate* plant. Lawre and Raskar [30] observed that TiO_2NPs at a lower concentration enhanced seed germination and seedling growth in onion plants. Rafique et al. [31] found a positive effect of TiO_2NPs on the *Triticum aestivum* plant. Mahmoodzadeh et al. [32] found a positive effect of TiO_2NPs on the seed germination of the *Brassica napus* plant. Qi et al. [33] reported that treatment of TiO_2NPs promotes photosynthetic rate in tomato plants.

Silicon is an important element that plays a key role in several metabolic and physiological activities in plants [34]. SiO_2nanoparticles have the potential to enhance the germination and seedling growth of *Agropyron elongatum* [35]. Nano-SiO_2 can be used to produce effective fertilizers for crops and to minimize the loss of fertilizer through slow and controlled release, allowing for regulated, responsive, and timely delivery [36]. Siddiqui et al. [37] found improved seed germination in the *Cucurbita pepo* plant after treatment with Nano SiO_2. Haghighi and Pessarakli [38] reported that Nano Si treatment on the tomato plant improves photosynthetic rate in treated plants.

Copper is an essential element for plant growth and development. Copper plays a key role in the activity of many plant enzymes. Copper nanoparticles (Cu NP) are used as antimicrobial agents, gas sensors, catalysts, electronics, etc. [39]. Wang et al. [40] found that CuO NPs improved photosynthesis in the *Spinacia oleracea* plant. Zhao et al. [41] reported that $Cu(OH)_2$NPs improved the antioxidant system of the *Lactuca sativa* plant. Shinde et al. [42] found that $Mg(OH)_2$NP treatment promotes seed germination and seedling growth in the *Zea mays* plant. Hussain et al. [43] reported that MgO NPs improve the antioxidant system in *Raphanus sativus* plants. Cai et al. [44] observed that MgO NPs can promote the plant growth of the Tobacco plant. Imada et al. [45] found that MgO NPs can induce resistance in the tomato plant.

Iqbal et al. [46] reported that AgNP treatment improved plant growth and tolerance to heat stress in the *Triticum aestivum* plant. Mehta et al. [47] found that AgNPs' foliar application enhanced growth and biomass in the *Vigna sinensis* plant. Pilon et al. [48] observed that chitosan NPs protect apple plants after post-harvest. Van et al. [49] found that chitosan NPs improve plant growth in Robusta coffee.

Das et al. [50] found that FeS_2 NPs improved seed germination in *Cicer arietinum*, *Daucus carota*, *pinacia oleracea*, *Brassica juncea*, and *Sesamum indicum* crops. The effects of various nanomaterials have been summarized in the following table (Table 1).

Table 1. Effect of various nanomaterials on plant physiology and growth parameters.

Nanoparticles	Plant	Effect on Plants in a Dose-Dependent Manner	Reference
Zn, B, Si, Zeolite NPs	Potato	Improve plant growth	[19]
ZnO NPs	Eggplant	Increase plant growth attributes	[20]
ZnO NPs	*Triticum aestivum*	Positive effect on seed germination	[21]
SiO_2 & TiO_2 NPs	Rice	Improve plant growth attributes	[22]
Nano-size calcite product [CaCO3(40%), SiO2(4%), MgO (1%), and Fe2O3(1%)]	Grapevine	Increase plant growth attributes and photosynthetic pigment	[23]
ZnO NPs	*Leucaena leucocephala*	Increase in photosynthetic pigment and total soluble protein contents	[24]
ZnO NPs	*Sesamum indicum*	High chlorophyll'a', chlorophyll'b', and total chlorophyll content level	[25]
ZnO NPs	*Zea mays*	Increased shoot dry matter and leaf area indexes.	[26]
ZnO NPs	*Pennisetum glaucum*	ZnO NPs enhanced shoot and grain yield	[27]
TiO_2 & ZnO NPs	Beetroot	Increased plant growth and shoot dry matter	[28]
TiO_2 NPs	*Vigna radiata* L.	Improvement was observed in shoot length	[29]
TiO_2 NPs	Onion	Lower concentration of TiO_2 NPs enhanced seed germination and seedlings growth	[30]
TiO_2 NPs	*Triticum aestivum* L.	Increase in the plant's root and shoot lengths	[31]
TiO_2 NPs	*Brassica napus*	Promoted seed germination and seedling vigor improved	[32]
TiO_2 NPs	Tomato	Promote the photosynthetic rate	[33]
SiO_2NPs	*Larix olgensis*	Increase in plant height, root length, and chlorophyll content	[34]
SiO_2NPs	*Agropyron elongatum* L.	Improve seed germination	[35]
Nano- SiO_2	*Cucurbita pepo* L.	Reduce the salt stress effect	[37]
Nano Si	Tomato	Enhancement of germination rate and dry weight	[38]
CuO NPs	Spinacia oleracea	Improved photosynthesis in treated plants	[40]
MgO NPs	Tobacco	Promote plant growth	[44]
MgO NPs	Tomato	Induce resistance in tomato plant	[45]
AgNPs	Wheat	Regulate antioxidative defence system	[46]
AgNPs	soil bacterial diversity	Regulate soil bacterial diversity	[47]
Chitosan NPs	Apples	They reduce microbial growth	[48]
Chitosan NPs	Robusta cofee	Improved growth parameters	[49]
FeS_2 NPs	*Cicer arietinum; pinacia oleracea; Daucus carota, Brassica juncea and Sesamum indicum*	Seed germination enhanced in tested crops	[50]
Chitosan NPs	Rice	Reduces disease severity	[51]
Chitosan NPs	Strawberry	Regulate defense response	[52]
SiNPs	*Helianthus annuus*	Improved germination	[53]
SilicaNPs	*Vicia faba* L.	Improved growth parameters	[54]
SiO_2NPs	Pea	Improved growth parameters and chlorophyll content	[55]
SiO_2 & MoNPs	Rice	Regulate seed germination	[56]
SiO_2NPs	*Indocalamus barbatus*	Improved photosynthetic pigments	[57]

Table 1. *Cont.*

Nanoparticles	Plant	Effect on Plants in a Dose-Dependent Manner	Reference
SilicaNPs	*Zea mays.* L	Improve silica content in plants	[58]
SiO_2NPs	Maize	Improved growth parameters and increased seed stability	[59]
$SiO_2$and TiO_2NPs	Soybean	Enhance germination of seeds	[60]
$Cu(OH)_2$	*Lactuca sativa*	Improve antioxidant system	[61]
$Cu(OH)_2$	Spinach	Improve the antioxidant system	[62]
ZnO NPs	*Glycine max*	Enhanced Antioxidant system	[63]
ZnO NPs	Cabbage, cauliflower, and tomato	Enhance pigments, protein, and sugar contents	[64]
ZnO NPs	*Arachis hypogaea*	Seed germination enhaced	[65]
FeS_2 NP	Spinach	Improve plant growth	[66]
TiO_2 NPs	*Glycine max* L.	Positive effect on the seed and oil yield and component compared to the control	[67]
TiO_2 NPs	*Mentha Piperita*	Increased root length	[68]
TiO_2 NPs	*Agropyron desertorum*	Improves seed germination	[69]

3. Nanomaterials in Various Diseases Management

Nanomaterials have antimicrobial activity. Silver nanoparticles have anti-bacterial and anti-fungal properties. Kim et al. [70] have reported the fungicidal effects of nano-silver against *Alternaria alternata, A. brassicicola, A. solani, Botrytis cinerea, Cladosporium cucumerinum, Corynespora cassiicola, Cylindrocarpon destructans, Didymella bryoniae, Fusarium oxysporum f. sp. cucumerinum, F. oxysporum f. sp. lycopersici, F. oxysporum, F. solani, Fusarium sp., Glomerella cingulata* and a few other fungi. Gautam et al. [71] showed the antifungal and antibacterial activity of AgNPs against *Erwinia sp., Bacillus megaterium, Pseudomonas syringe, Fusarium graminearum, F. avenaceum,* and *F. culmorum* fungi. Rodríguez-Serrano et al. [72] reported the antibacterial activity of AgNPs against *E. coli*. Husseinet al. [73] reported the antibacterial activity of AgNPs against *Staphylococcus aureus* and *Klebsiella pneumonia*. Shehzad et al. [74] reported that AgNPs have antibacterial activity against Gram-positive (*Bacillus subtilis*) and Gram-negative (*Escherichia coli*) bacteria. Mohanta et al. [75] reported that AgNPs have antibacterial activity against food borne pathogens *Pseudomonas aeruginosa, Escherichia coli,* and *Bacillus subtilis*. Abdelmale and Salaheldin [76] reported that AgNPs show antifungal activity against *Alternaria alternata, A. citri,* and *Penicillium digitatum* fungi. Krishnaraj et al. [77] found theantifungal activity of AgNPs against *Alternaria alternata, Macrophomina phaseolina, Botrytis cinerea, Sclerotinia sclerotiorum, Curvularia lunata,* and *Rhizoctonia solani* fungi. Jo et al. [78] described the antifungal activity of AgNPs against *Bipolaris sorokiniana* and *Magnaporthe grisea* fungi.

Shahryari et al. [79] reported that AgNPs and a silver–chitoson composite show antibacterial activity against *Pseudomonas syringae* pv. *syringae* bacteria. Divya et al. [80] reported that chitoson NPs have antifungal activity against *Macrophomia phaseolina* and *Alternaria alterneta* fungi. Xing et al. [81] reported that chitoson NPs have antifungal activity against *Fusarium solani* and *Aspergillus niger* fungi. Dang et al. [82] reported that AuNPs have antibacterial activity against *E. coli* bacteria. Attar and Yapaoz [83] observed that ZnO and AuNPs have antibacterial activity against *E. coli* bacteria. The gold nanoparticles showed toxic effect on bacteria, *Salmonella typhimurium*, in which the macro gold did not exhibit. Jayaseelana et al. [84] synthesized gold nanoparticles from *Abelmoschus esculentus* and reported their antifungal activity. The antifungal activity of AuNPs was tested against *Puccinia graministritci, Aspergillus niger, Aspergillus flavus* and *Candida albicans* using the standard well diffusion method. The maximum zone of inhibition was observed in the Au NPs against *P. graminis* and *C. albicans*.

Fan et al. [85] observed the antibacterial activity of Cu composites against *Xanthomonas euvesicatoria.* Huang et al. [86] showed the antifungal activity of CuO NPs against *Botrytis cinerea, Colletotrichum graminicola, Rhizoctonia solani, Colletotrichum musae, Magnaporthe oryzae, Penicillium digitatum*, and *Sclerotium rolfsii.* Giannousiet al. [87] showed the antifungal activity of CuO and Cu_2O NPs against *Phytophthora infestans.* Sharmaet al. [88] reported the antifungal and antibacterial activity of MgONPs against *Ralstonia solanacearum* bacteria and *Phomopsis vexans* fungus. Imada et al. [45] found the antibacterial activity of MgONPs against *Ralstonia solanacearum*. Derbalah et al. [89] observed the antifungal property of silica NPs against *Alternaria solani* fungus. Akpinar et al. [90] found that SiO_2 NPs possess antifungal properties against *Fusarium oxysporum* f. sp. *lycopersici* and *F. oxysporum* f. sp. *radicislycopersici.* Park et al. [91] showed the antifungal activity of Nano Si-Ag against *Pythium ultimum, Magnaporthe grisea, Colletotrichum gloeosporioides, Botrytis cineria, Rhizoctonia solani, Pseudomonas syringae*, *Xanthomonas compestris* pv. *vesicatoria*.

Jamdagni et al. [92] found that ZnO NPs have promising antifungal activity against *Alternaria alternate Botrytis cinerea, Aspergillus niger, Fusarium oxysporum,* and *Penicillium expansum* fungi. Navale et al. [93] found the promising antifungal activity of ZnO NPs against *Aspergillus flavus* and *Aspergillus fumigates* fungi. Rajiv et al. [94] reported the antifungal activity of ZnO NPs against *Aspergillus flavus*, *A. niger*, *A. fumigates*, *Fusarium culmorum*, and *F. oxysporium.* Gunalan et al. [95] found that ZnO NPs have promising antifungal activity against *Aspergillus flavus, Trichoderma harzianum, A. nidulans*, and *Rhizopus stolonifer.* Dimkpa et al. [96] have shown the antifungal activity of ZnO nanoparticles on *Fusarium graminearum* fungus. Jayaseelan et al. [97] synthesized ZnO nanoparticles using *Aeromonas hydrophila* and screened their activity against pathogenic bacteria *P. aeruginosa*, and fungi, *C. albicans*, *A. flavus*, and *A. niger*. Sar et al. [98] reported the antifungal activity of TiO_2 NPs against *Fusarium oxysporum* f. sp. *radicislycopersici* and *Fusarium oxysporum* f. sp. *Lycopersici.* Hamza et al. [99] found the antifungal activity of TiO_2 NPs against *Cercospora beticola.* Ardakani [100] found the nematicidal activity of TiO_2 NPs against *Meloidogyne incognita* nematode. Kasemets et al. [101] reported the antifungal activity of ZnO and TiO_2 NPs against *Saccharomyces cerevisiae.* Cui et al. [102] found that TiO_2 NPs have antibacterial against *P. syringae pv. lachrymans and P. cubensis* (Table 2, Figure 3).

Table 2. Various nanomaterials in plant disease management

Nanoparticle	Pathogen	Effect	Reference
Ag NPs	*Alternaria alternata, A. brassicicola, A. solani, Cladosporium cucumerinum, Botrytis cinerea, Corynespora cassiicola, Cylindrocarpon destructans, Didymella bryoniae, F. oxysporum f. sp. lycopersici, F. oxysporum, Fusarium oxysporum f.sp. cucumerinum, F. solani, Fusarium sp., Glomerella cingulata, P. spinosum, Monosporascuscannonballus, Pythium aphanidermatum, Stemphylium lycopersici*	Show antifungal activity	[70]
AgNPs	*Erwinia sp., Bacillus megaterium, Pseudomonas syringe, Fusarium graminearum, F. avenaceum, F. culmorum*	An inhibitory effect on tested microbes	[71]
AgNPs	*Escherichia coli*	Antibacterial activity	[72]
AgNPs	*Staphylococcus aureus* and *Klebsiella pneumonia*	Antibacterial activity	[73]
AgNPs	Gram-positive (*Bacillus subtilis*) and gram-negative (*Escherichia coli*).	An inhibitory effect on tested bacteria	[74]
AgNPs	Foodborne pathogens viz. *Pseudomonas aeruginosa*, *Escherichia coli*, *Bacillus subtilis.*	Antibacterial activity	[75]
AgNPs	*Alternaria alternata, A. citri, Penicillium digitatum*	Show antifungal properties	[76]
AgNPs	*Alternaria alternata, Macrophomina phaseolina, Botrytis cinerea, Sclerotinia Sclerotiorum, Curvularia lunata, Rhizoctonia solani*	Show Antifungal activity.	[77]

Table 2. *Cont.*

Nanoparticle	Pathogen	Effect	Reference
AgNPs	*Bipolaris sorokiniana* and *MagnaportheGrisea*	Show antifungal activity	[78]
AgNPs and Cs-Ag nanocomposite	*Pseudomonas syringaepv.syringae*	Show antibacterial activity	[79]
Chitosan NPs	*Klebsiella pneumoniae, Escherichia coli, Staphylococcus aureus, Pseudomonas aeruginosa*	Show antibacterial activity	[80]
Chitosan NPs	*Fusarium solani, Aspergillus niger*	Show Antifungal activity	[81]
Au NPs	*Escherichia coli* and *Staphylococcus*	Antibacterial activity	[82]
ZnO and Au NPs	*E. coli*	Antibacterial activity	[83]
AuNPs	*Puccinia graminis tritci, Aspergillus flavus, Aspergillus niger and Candida albicans*	Show Antifungal activity	[84]
Cu composites	*Xanthomonas euvesicatoria*	Antibacterial activity	[85]
CuO NPs	*Botrytis cinerea, Colletotrichumgraminicola, Rhizoctonia solani, Colletotrichum musae, Magnaportheoryzae, Penicillium digitatum, Sclerotium rolfsii*	Show antifungal activity	[86]
CuO and Cu_2O NPs	*Phytophthora infestans*	Show antifungal activity	[87]
MgO NPs	*Ralstonia solanacearum, Phomopsis vexans*	Show antifungal and antibacterial activity	[88]
SilicaNPs	*Alternaria sp*	Show antifungal activity	[89]
SiO_2 NPs	*Fusarium oxysporum* f. sp. *lycopersici* and *F. oxysporum* f. sp. *radicislycopersici*	Possess antifungal properties	[90]
Nano Si-Ag	*Pythium ultimum, Magnaporthe grisea, Colletotrichum gloeosporioides, Botrytis cineria, Rhizoctonia solani, Pseudomonas syringae, Xanthomonas compestris* pv. *vesicatoria*	Show antifungal and antibacterial activity	[91]
ZnO NPs	*Alternaria alternate Botrytis cinerea, Aspergillus niger, Fusarium oxysporum* and *Penicillium expansum*	Antifungal activity against all the tested fungi	[92]
ZnO NPs	*Aspergillus flavus* and *Aspergillus fumigates*	Shown potential activity against these tested fungi	[93]
ZnO NPs	*Aspergillus flavus, A. niger, A. fumigatus Fusarium culmorum* and *F. oxysporium*	The highest zone of inhibition occurred in *A. flavus*	[94]
ZnO NPs	*Aspergillus flavus, A. nidulans, Trichoderma harzianum* and *Rhizopus stolonifer*	Antifungal activity	[95]
ZnO NPs	*Fusarium graminearum*	Antifungal activity	[96]
ZnO NPs	*Pseudomonas aeruginosa*	Antibacterial activity	[97]
TiO_2 NPs	*Fusarium oxysporum* f. sp. *radicislycopersici* and *Fusarium oxysporum* f. sp. *Lycopersici*	Antifungal activity	[98]
TiO_2 NPs	*Cercosporabeticola*	Pathogen growth was inhibited	[99]
TiO_2 NPs	*Meloidogyne incognita*	Controlled *M. incognita*	[100]
TiO_2 NPs and ZnO NPs	*Saccharomyces cerevisiae*	Antifungal activity	[101]
TiO_2 NPs	*P. syringaepv. lachrymans and P. cubensis*	Reduced infection of pathogen	[102]
Metallic NPs	*Fungus and Bacteria*	Antibacterial and antifungal activity	[103]
Metallic NPs	*Microbes*	Antibacterial and antifungal activity	[104]
AgNPs	*Fusarium culmorum*	Antifungal activity	[105]

Table 2. *Cont.*

Nanoparticle	Pathogen	Effect	Reference
Chitosan NPs	*Streptococcus*	Antibacterial activity	[106]
AuNPs	*Candida albicans*	Antifungal activity	[107]
AuNPs	*Escherichia coli*, *Staphylococcus aureus*	Antibacterial activity	[108]
ZnO NPs	*Ralstonia solanacearum*	Antibacterial activity	[109]
ZnO NPs	*Botrytis*, *Escherichia*	Antibacterial and antifungal activity	[110]
ZnO NPs	*Fusarium oxysporum*, *Aspergillus niger*	Antibacterial and antifungal activity	[111]
ZnO NPs	*Alternaria alternate, Fusarium oxysporum, Rhizopus stolonifer* and *Mucor plumbeus*	Inhibit germination of spores of fungi	[112]
ZnO NPs	*Botrytis cinerea* and *Penicillium expansum*	Significantly inhibit growth	[113]
ZnO NPs	*Psedomanas* sp. and *Fusarium* sp.	Antibacterial and antifungal activity	[114]
TiO_2 NPs	*Xanthomonas hortorum* pv. *pelargonii*, *X. axonopodis* pv. *Poinsettiicola*	Antibacterial activity	[115]

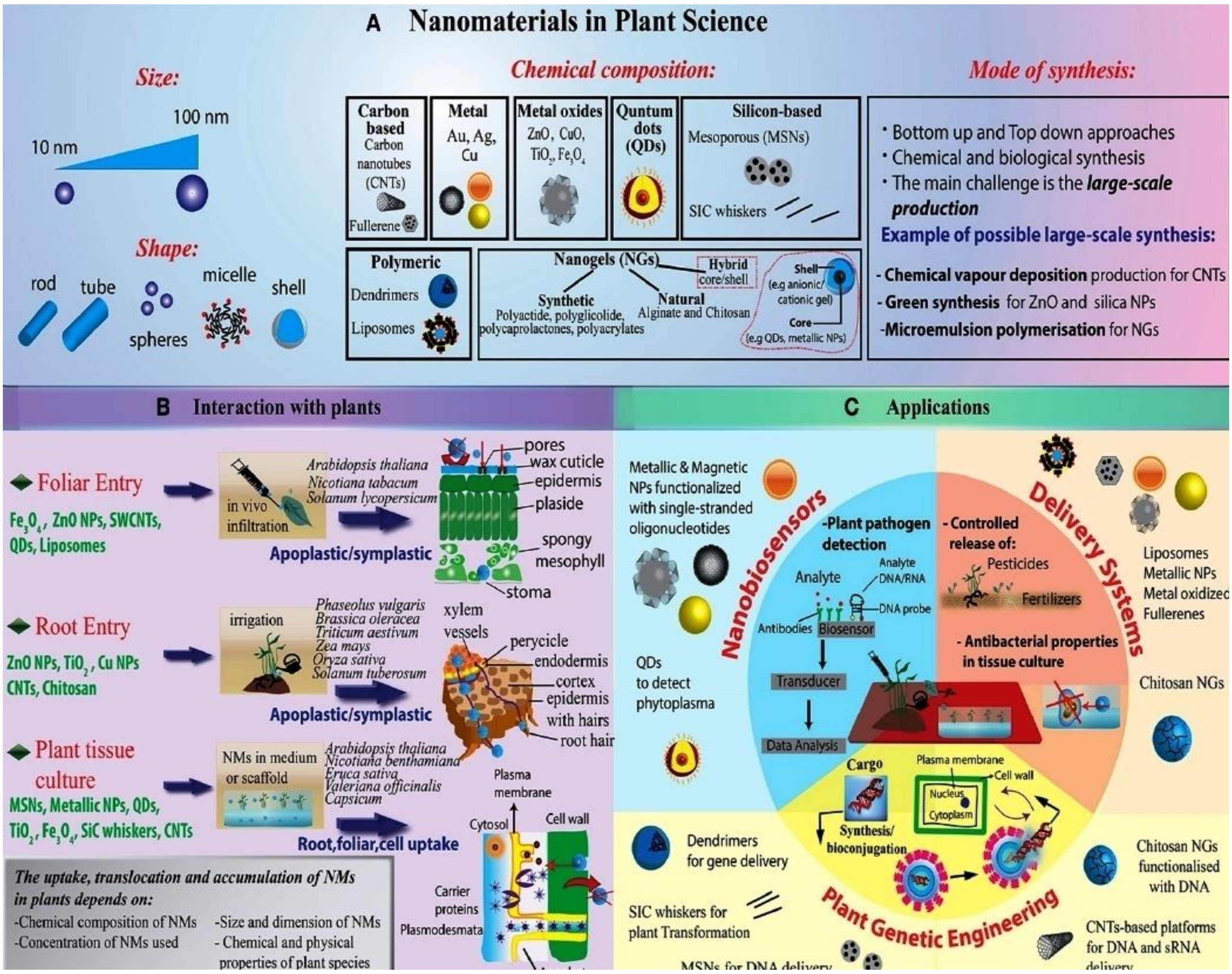

Figure 3. (**A**) Different types of nanoparticles. (**B**) Schematic presentation of delivery methods of different nanoparticles and translocation in plants. (**C**) Various applications of nanoparticles (Taken from Sanzari et al. [116]).

The inhibitory action of nanoparticles on fungi and bacteria includes disruption by pore formation in the cell membrane, disturbance in membrane potential, cell wall damage, direct attachment to the cell surface, DNA damage, cell cycle arrest, the inhibition of enzyme activity and reactive oxygen species (ROS) generation, and this finally leads to death. Nanoparticles generate the ROS, which causes damage to the cellular structures. The different components of reactive oxygen species include free radicals, such as hydrogen peroxide (H_2O_2), superoxide (O_2^-), singlet oxygen ($^1O_2$), carbon dioxide radical (CO_2^-), hydroxyl ($HO^·$), hydroperoxyl (HO_2), carbonate (CO_3^-), peroxyl (RO_2), and alkoxyl (RO), and non-radicals, such as ozone (O_3), nitric oxide (NO), hypobromous acid (HOBr), hypochlorous acid (HOCl), hypochlorite (OCl^-), peroxy nitrite ($ONOO^-$), organic peroxides (ROOH), peroxo monocarbonate ($HOOCO_2^-$), peroxy nitrous acid (ONOOH) and peroxy nitrate (O_2NOO-), and these nanoparticles accumulate in the membrane of bacteria or fungi, which leads to change in the permeability of the cell membrane and disturbs the proton motive force (PMF).Oxidative stress due to the higher concentration leads to single- and double-strand breaks and nitrogen base and pentose sugar lesions [103,104].

4. Toxic Effect of Nanoparticles

Nanomaterials' effect on organisms is largely dependent on the dose, size, and shape, the types of NPs, concentration, and the duration of exposure to NPs and the plant/animal species [117,118]. Nanoparticles at optimum concentration augment the plant's growth, but high concentrations of nanoparticles could be toxic for plants. Kushwah and Patel [119] observed that the optimum concentration of nano TiO_2 in the *Vicia faba* plant ranged from 5–50 mg/L. Other studies proved that TiO_2 NPs may induce stress in plants such as tomato, cucumber and spinach at high concentration [120]. Silver nanoparticles cause chromosomal aberrations in *Vicia faba* [121]. Lopez-Moreno et al. [122] reported that CeO_2 nanoparticles can induce DNA damage in soybean.

5. Conclusions

In summary, the literature shows that food demands will increase with time, and to fulfill the demand of people, the present agricultural practices are not sufficient and chemicals used in agriculture as pesticides have a severe toxic effect on the environment. Thus, we need to develop an alternative approach that has a less toxic effect on the environment and that could help in fulfilling food demands. According to estimates, around 192.8 Mt chemical fertilizers were used in 2016–2017 in the whole world. The use of toxic chemicals and pesticides causes environmental pollution, which affects fauna and flora. Pathogens and pests induce resistance against fungicides and pesticides. Hence, optimizing of the use of toxic chemical pesticides and fungicides is needed. Nanotechnology is flamboyant and has provided nanostructure materials as pesticide and fertilizer carriers. Nanomaterials can develop smart fertilizers as they can enhance nutrient availability and reduce environmental pollution [123]. Novel nanotechnology can be an alternative that can reduce crop diseases and enhance crop yield. Previous studies reported a significant positive effect of nanomaterials on crop plants. This novel technology can reduce the use of toxic chemicals and pesticides that contaminate soil, the environment, and groundwater. Further research is needed to develop this technology on a large scale (Figure 4).

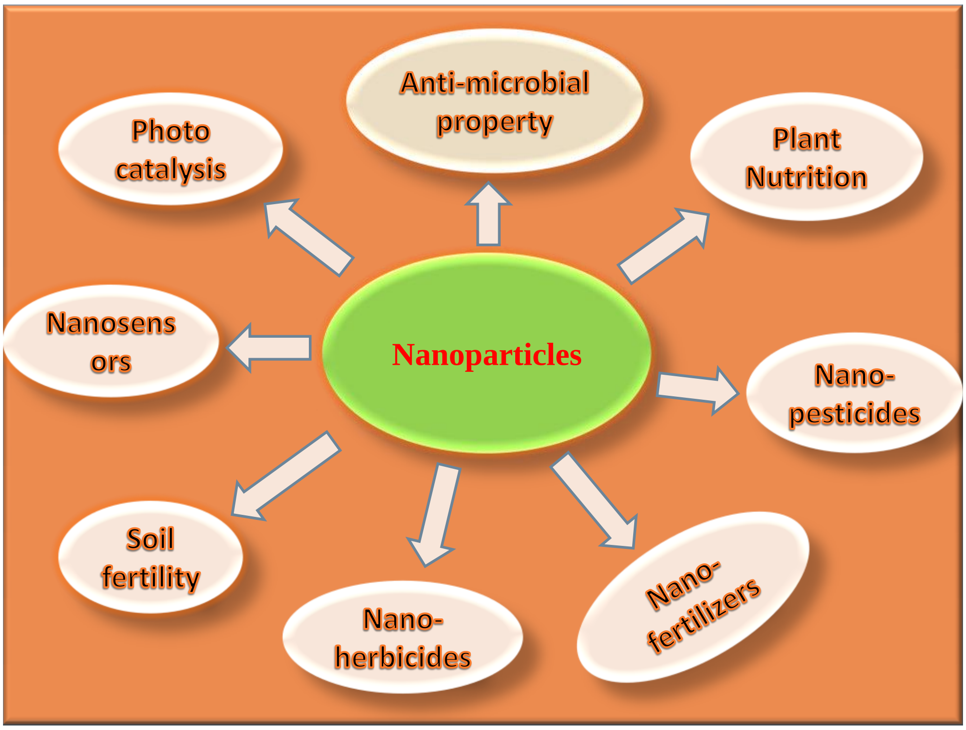

Figure 4. Diagram showing general applications of nanoparticles in agriculture.

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