NanoWorld Journal

https://doi.org/10.17756/nwj.2022-100

Research Article

Open Access

A Review on Wide Range Application of Nanoparticles in Agriculture and its Implications in Plant Disease Management

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Received: April 13, 2022
Accepted: June 14, 2022
Published: June 17, 2022

Citation: Vaghasiya TP, Kumar A, Nakum K. 2022. A Review on Wide Range Application of Nanoparticles in Agriculture and its Implications in Plant Disease Management. *NanoWorld J* 8(2): 55-65.

Published by United Scientific Group

Abstract

In the current situation several types of synthetic pesticides are available but they are harmful for the ecosystem and do possess a devastating impact on human health. The other side organic fungicides and biocontrol agents are also accessible in the market which relies on specific environmental conditions and can be used only under particular situations. Most of the organic methods are slow and time-consuming processes and contrary farmers don't have time as biological processes of the plants are fast, so the timing is foremost valuable for economic yields. To combat the existing situation there is an alternate solution exists in the form of nano technology for the management of plant pathogens and currently nano fungicides i.e., AgNps, CuNPs, TiO_2, chitosan nanoparticles and nano emulsions are being used in the sector of plant diseases management. These days' nanoparticles are used in the agriculture sector because of their antifungal, antibacterial and antiviral properties. Nano silvers (silver nanoparticles) and nano sensors are applied against abiotic stresses and insect pests as fertilizers, growth promoters and insecticides respectively. Presently many researches were conducted on silver particles and silver nano-based fungicides show high effectivity against plant pathogens. Hopefully in the future, silver nanoparticles will be marketed for the control of plant diseases and insect pests and for the detection of pesticides. Therefore, this manuscript addresses all the possible applications and approaches of nanoparticles as effective and ecofriendly tools imparting growth to the plants which reduces impact of plant diseases on plant part as plant system is strengthen and to combat against plant pathogens & insect pests because of their antifungal, antibacterial, antiviral & insecticidal properties.

Keywords

Nanotechnology, Nanoparticles, Synthetic fungicides, Ecosystem, Human health

Introduction

Worldwide loss to the yield due to insect pests, diseases and weeds is 14, 13 and 13 percent respectively [1]. An average worldwide yield loss due to plant diseases every year estimated 2,000 billion dollars [1] wherein only fungi cause 200 billion US dollar loss in a year [2]and pesticides are the sources of management of plant diseases, and these synthetic pesticides undoubtedly cause severe health concerns to humans and animals via treated plant produce and products [3]. In India, total consumption of pesticides was 60,566 MT in the financial year 2019-2020 [4].

A good economic and widely accepted alternate to synthetic pesticides can be use of a nano technological approach which may termed as nano-agriculture in which nanoparticle or nano-size materials are used to enhance crop productivity and suppress the pest [5, 6]. Nanotechnology has all the potential to improve plants yield [7], detect plant pathogens [8], protect plants [9], increase food production [10] and improve food quality [11].

Metals play an important role in the plant management; application of direct metal can cause phytotoxic effects to plants but once it was used with nanotechnology improves plant's quality and quantity [12]. Nano agriculture lies on various types of metals like silver [13], silica [14], sulphur [15], gold [16], titanium [17] etc. but silver particles has been widely used since very long time because of its antimicrobial and anti-viral properties [18-23] also silver nanoparticles are hydrophilic in nature so disperse easily and distribute uniformly in water [24, 25]. Though the medical use of silver has been documented long back since 1000 B.C and Chinese and Indian Ayurveda has recommended silver as medicine to maintain good health [26]. Silver (Ag) metal elements have atomic number 47 and atomic mass 107.87. The average Ag content in the soil is 100 ng g^{-1} and ranging from 10 to 5,000 ng g^{-1} [27].

Nanotechnology in Agriculture

Agriculture is a broad term that includes various types of systems to cultivate plants. Nanotechnology has been used since the last half-century, but its application and implantation started in recent years in agriculture [28]. In agriculture, nanotechnology is being a very useful and eco-friendly tool for soil, air and water management; bubble chart depicts multi-dimensional application of nanomaterial for crop protection, crop production, management of crops and food processing [29].

Nanotechnology and crop production

Used for monitoring of crops

Nanotechnological tools or machines are used these days for the supervision of crops. In the nanotech field, they develop nanosensors wherein the sensing capacity is less than 100 nm in the depth of material [30]. Nanosensors determine the chemical and physical changes in the soil and plant ecosystems, available soil and plant nutrient status and detect the presence of plant pathogens, weeds and insect pests in the field [31, 32]. Nanotechnology also helps the detection of pesticides for instance Surface-enhanced Raman scattering (SERS) technology, in this technology Au and Ag is used to detect Thiacloprid, Profenofos and Oxamyl [33]. Use of gold and silver nanoparticles to detect organophosphate pesticides into the environment was executed effectively (Simolian et al. [34]. Humic acid protected nanoparticles are sensitive to an increased amount of sulfurazon-ethyl herbicide and the particle changes color of solution yellow to purple and acts as nanosensor and herbicide detector [35]. Nanotechnology is also useful for suppression of pollution wherein the nanoparticles are used to treat soil, sediment, wastewater and, control air pollution for instance Chitosan and silver combination is used as a filter of drink water and remove pesticide particles from the wastewater [36]. Nanoparticles are also used for the mineralization of halocarbons and other organic as well as inorganic contaminants [37].

Used as fertilizers

In the conventional application methods like spraying and broadcasting which cause losses by leaching, runoff, evaporation, microbial and photolytic degradation. In these conventional methods, fewer amounts of fertilizers get available to the plants wherein about 40-70% Nitrogen, 80-90% Phosphorus and 50-90% potassium get lost in the environment [38]. Due to this loss of fertilizers farmers apply more fertilizers which cause pollution, reduction of microflora and have residual effect on plant produce. These losses can be solved through Nano fertilizers; fertilizers are being used in combination with nanomaterials. Nanomaterials are beneficial and give better performance when compared with synthetic fertilizers regarding the plants [39] for instance use of magnetic fields with silver nanoparticles improve growth and quality of fodder maize crops [40].

Used as growth promoters

When nanofertilizers were used in adverse conditions for the improvement of plant's growth, improvement of germination rate, germination percentage, dry weight and root length was observed. AgNPs treated tomato plants under two levels of salinity [100 ppm and 150 ppm] found incorporating and increasing growth and yield of tomato plants [41]. Razzaq and teammates [42] stated that silver nanoparticles have potential to improve plant growth and yield with a low concentration (25 to 50 ppm), silver nanoparticles with the combination of gold nanoparticles improve leaf area, number of leaves, plant height, chlorophyll content and sugar content that led to improving yields [43-45]. Silver nanoparticles at 50 ppm concentration in black mustard seeds improve shoot length and root length of the plant [146]. Seeds coated with silver nanoparticles absorb more water in comparison to uncoated seeds [47] and seeds treated with AgNPs could show 90% more resistance then untreated under drought conditions [48].

Used in genetics and tissue culture

Silver nanoparticles are also used in gene regulation, for instance a sublethal dose of silver nanoparticles was not found having direct effect on N_2 fixing (anfD, nifH, nifD, vnfD) and N_2 denitrifying (napB, norB, nirH, narG) genes but other involved genes (amoA1, amoC2) in nitrification is upregulated in *Nitrosomonas europaea* [49]. In tissue culture, the use of silver nanoparticles in callus formation, root and shoot generation have been reported, for instance *Tecomella undulata* explant medium with the use of silver nanoparticlefound increasingnumber of shoots and the formation of callus [50-52]. Silver nanoparticles also improve the quality of the plant when used astissue culture methods, for instance variety *Solanum nigrum* was improved by somaclonal variationwith the use of silver nanoparticles [53].

Nanotechnology and crop protection

Now a day pesticides or synthetic chemicals are used in a large amount in the agriculture sector for the management of plant diseases, insect pests and weeds. This excess use of synthetic chemicals does have harmful effects on the ecosystem as it causes mortality, modifications in beneficial fauna and flora and develop resistance into pests of plants [54]. When the use of nanoparticles integrated with other chemicals it has negligible adverse effect on the ecosystem and found reducing toxicity in fauna and flora [55] and humans [56, 57].

Used in management of Insect pests

Silver nanoparticles synthesized from *Azadirachta indica* were used to control mosquito larvae as it has hydrophilic nature and insecticidal properties; AgNPs used against *Aedes aegypti* and *Anopheles stephensi* [58]. Sap-Iam and colleagues also used UV-induced silver nanoparticles to kill mosquito larvae as a larvicide [59]. Silver nanoparticles were also integrated with insecticides like, Dichlorvos and Chlorpyrifos to enhance their insecticidal properties and effectiveness; 95% and 98% in Dichlorvos and Chlorpyrifos respectively [60]. According to Yang and colleagues, use of nanoparticles with the garlic oil is effective against *Tribolium castaneum* (Herbst) [61]. Nanosilvers affect larva of *Callosobruchus maculatus* and silica nanoparticles affect adult stage while experimenting with silver and sulphur nanoparticles found effective against the different stages of *Drosophila melanogaster* [62]. Table 1 show nanoparticles used worldwide in the management of insect pests of crops.

Used in management of plant pathogens

Silver nanoparticles (AgNPs) have become one of the most commonly used nanomaterials in consumer products, and for several decades, silver (Ag^{+}) has been studied as an antimicrobial agent against various harmful microorganisms [60]. Being powerful disinfectant agent silver nanoparticles (AgNPs) have antiviral [63], antifungal [64], antibacterial [65] properties and became one of the most used nanomaterials in the management of plant diseases.

Management of fungal diseases

Nanoemulsions like polyvinyl chloride, polyvinyl pyridine and chitosan, Nanoclays and Nanoparticles like ZnO, Ag and Ag^{+}, TiO_2, CeO_2, Au, Al, Fe and CuO are the nanotechnologies used with fungicides in the management of plant diseases [66]. In nano fungicides many metals like Au, Ag, Au-Ag alloy [67], selenium [68], tellurium [69], platinum [70] are used to control the plant pathogens, in those metals silver is very efficient to control plant pathogens.

The smaller nanosilver particles are more effective at inhibiting fungal growth because it easily passes through the cell wall [71]. According to Kim and teammates, silver with silica nanoparticles inhibited more than 90% growth of *Rhizoctonia solani* at 6 µg/ml concentrations [72, 73]. Ouda and colleagues stated that use of AgNPs with CuNPs was effective against *Alternaria alternata* and *Botrytis cinerea* [74]. Karimi and Sadeghi found that 100 ppm concentration of AgNPs inhibited 100% growth of *Pythium aphanidermatum, Botrytis cinerea, Pythium spinosum, Coletrotricum cucumerinum, Glomerella cingulata, Cylindrocarpon destructans, Fusarium oxysporum* f.sp. *cucumerinum, Monosporascus cannonballus* and *Fusarium oxysporum* [75]. Aziz and his team found that use of biogenic silver nanoparticles showed better results compared to chemical fungicides like fluconazole, ketoconazole and amphotericin B [20, 76].

Mode of action: There are several mechanisms through which silver nanoparticles are used to control plant diseases. There are numerous theorieson mechanisms of working of silver nanoparticles; causestructural changes incellularmechanism and cause cell death [76], interact with thiol (-SH) group to inhibit and inactivate enzymes [77, 78], inhibit respiratory enzymes in DNA and Protein contain sulphur and phosphorus [79-83]. They can increase the permeability of cell membranes by producing reactive oxygen speciesand interrupt in replica-

Table 1: Silver nanoparticles and their combination with other material for the management of insect pests.

Insect	Combination	Reference
Chironomus riparius (Meigen)	-	[124]
Aedes albopictus	*Cassia fistula* extract	[125]
Culexpipiens pallens	*Cassia fistula* extract	[125]
Aedes albopictus	Salicylic acid and 3,5-dinitrosalicylic acid	[126]
Drosophila melanogaster	-	[127, 128]
Spodoptera litura	-	[129]
Achaea janata	-	[129]
Spodoptera litura	*Punica granatum*	[130]
Lipaphis erysimi Kalt.	*Beauveria bassiana*	[131]
Tribolium castaneum	Malathion	[132]
Sitophilus oryzae	*Euphorbia prostrata*	[133]
Pericallia ricini	Gold nanoparticle	[134]
Aphis nerii	Zinc nanoparticle	[135]
Agrotis ipsilon	*Bacillus thuringiensis kurstaki* (Btk)	[136]
Trichoplusia ni (Hübner)	*Bacillus thuringiensis kurstaki* (Btk)	[136]
Corcyra cephalonica (S.)	*Ocimum sanctum*	[137]

tion of deoxyribonucleic acid [84]. Table 2 and 3 show silver nanoparticles and their combination with other nanoparticles used for the management of fungal plant pathogens.

Management of bacterial diseases

Silver nanoparticles are known for strong bacteriostats, Bactericidal and broad-spectrum antimicrobial activity [85, 86]. Silver nanoparticles also affect soil plant pathogenic bacteria [87] and act as strong antimicrobial agents due to inhibitory effects against various bacteria [88-90]. Silver and TiO_2 nanoparticles in combination are effective for removing bacterial pathogens from tobacco plants [91]. The bacterium, *Xanthomonas perforans* (tomato) was reported developing resistance against Cu fungicides but when low concentration (16 ppm) of silver nanoparticles with Graphene oxide were used, inhibited bacterial spot diseases of tomato [92].

Mode of action: Owing to electrostatic attraction and affinity to sulfur proteins, silver ions can adhere to the cell wall and cytoplasmic membrane. The adhered ions can enhance the permeability of the cytoplasmic membrane and lead to disruption of the bacterial envelope [93, 94]. Those silver irons also have inbuilt properties to bind with thiol (-SH) group of enzymes and inactive them [78]. Pathogen cells come in contact with silver irons, which inhibits many functions that lead to

Table 2: Silver nanoparticles against fungal plant pathogens.

Name of pathogen	Diseases name	Crop	Reference
Alternaria alternata	Alternaria blight	Strawberry, Chilli, Tomato	[73, 138]
Sclerotinia sclerotiorum	-	-	[138, 139]
Macrophomina phaseolina	-	-	[138]
Rhizoctonia solani	-	-	[72, 138, 139]
Botrytis cinerea	Gray mold	Brinjal, tomato, potato, Capsicum, strawberry	[73, 138]
Curvularia lunata	-	-	[138]
Sphaerotheca pannosa var *rosae*	Powdery mildew	Rose	[85]
S. minor	-	-	[139]
Fusarium graminearum	-	-	[140]
Fusarium udum	-	-	[140]
B. sorokiniana		Wheat	[141]
Sphaerotheca fusca	-	-	[142]
Fusarium culmorum	-	-	[143]
Alternaria brassicicola	Black spot	Cauliflower, radish, cabbage, kale	[73]
Alternaria solani	leaf spot	Capsicum, tomato, Brinjal, potato	[73, 144, 145]
Cladosporium cucumerinum	Scab	Brinjal, cucumber, pumpkin, melon	[73]
Corynespora cassiicola	Leaf spot	Capsicum, cucumber, bean, tomato, sesame	[73]
Cylindrocarpon destructans	Root rot	Strawberry, ginseng, peony	[73]
Didymella bryoniae	Black rot	Cucumber, pumpkin, watermelon, melon	[73]
Fusarium oxysporum f. sp. *cucumerinum*	Fusarium wilt	Cucumber	[73]
Fusarium oxysporum f. sp. *lycopersici*	Fusarium wilt	Tomato	[73]
Fusarium solani	Fusarium wilt	Potato, ginseng	[73]
Glomerella cingulata *Monosporascus*	Anthracnose	Pepper, strawberry, grapevine	[73]
Monosporascus cannonballus	Root rot	Cucumber, pumpkin, watermelon, melon	[73]
Pythium aphanidermatum	Damping-off	Tomato, tobacco, radish	[73]
Pythium spinosum	Root rot	Sweet potato, pumpkin, cabbage Eggplant,	[73]
Stemphylium lycopersici	Leaf spot	Eggplant, tomato, pepper	[73]
Alternaria niger	-	-	[146]
Alternaria flavus	-	-	[146]
Fusarium verticillioides	-	-	[148]
Fusarium moniliforme	-	-	[147]
Penicillium brevicompactum	-	-	[147]
Helminthosporium oryzae	-	-	[147]
Pyricularia grisea	-	-	[147]

Table 3: Combined applications of silver nanoparticles with other materials against fungal plant pathogens.

Combination with other material	Pathogen	Diseases	Crop	Reference
DHPAC shell nanocluster	*Phytophthora capsici*	-	-	[148]
DHPAC shell nanocluster	*tPhytophthora nicotianae*	-	-	[148]
DHPAC shell nanocluster	*Phytophthora colocasiae*	-	-	[148]
Trichoderma spp.	*Fusarium oxysporum* f.sp. *lycopersici*	Wilt	Tomato	[149]
Trichoderma spp.	*Sclerotium rolfsii*	Blight	Tomato	[149]
Fluconazole	*Phoma glomerata*	-	-	[150]
Fluconazole	*Phoma herbarum*	-	-	[150]
Fluconazole	*Fusarium semitectum*	-	-	[150]
Fluconazole	*Trichoderma* sp.	-	-	[150]
Fluconazole	*Candida albicans*	-	-	[150]
Neem	*Alternaria zinniae*	Leaf spot	Merigold	[151]
Ephobia	*Alternaria zinniae*	Leaf spot	Marigold	[151]
Silica	*Pythium ultimum*	-	-	[112]
Silica	*Magnaporthe grisea*	-	-	[112, 141]
Silica	*Colletotrichum gloeosporioides*	-	-	[112]
Silica	*Botrytis cinerea*	-	-	[112]
CuNPs	*Alternaria alternata*	-	-	[74]
CuNPs	*Botrytis cinerea*	-	-	[74]
Chloramphenicol	*Citrobacter freundii*	-	-	[12]
Chloramphenicol	*Erwinia cacticida*	-	-	[152]
Silica	*Podosphaera xanthii*	Powdery mildew	Cucurbits	[112]
SIO2	*Rhizoctonia solani*	-	-	[73, 112]
Chitosan	*Rhizoctonia solani*	-	-	[153]
Chitosan	*Aspergillus flavus*	-	-	[153]
Chitosan	*Alternaria. alternata*	-	-	[153]
Chitosan	*Colletotrichum gloeosporioides*	Anthracnose	Mango	[154]

Table 4: Silver nanoparticles against bacterial plant pathogens.

Name of pathogen	Diseases name	Crop	Ref.
Xanthomonas campestris pv. *campestris*	Black rot	Cabbage	[88, 155]
Bacillus megaterium	-	-	[156]
Pseudomonas syringae	-	-	[156]
Burkholderia glumae	-	-	[156]
Xanthomonas oryzae	-	-	[156]

Table 5: Combined applications of silver nanoparticles with other materials against bacterial plant pathogens.

Combination with other material	Pathogen	Reference
Graphene oxide	*Xanthomonas performance*	[92]
Silica	*Pseudomonas syringae* pv *syringae*	[112]
Silica	*Xanthomonas campestris* pv. *Vesicatoria*	[112]
Silica	*Bacillus subtilis* 1021	[112]
Silica	*Rhizobium tropici*	[112]
Silica	*Esterichia coli*	[112]

generation of reactive oxygen species (ROS) and cause inhibition in respiratory enzymes. Silver nanoparticles can prevent replication and protein synthesis [95], DNA contains sulfur and phosphorus as major components, silver nanoparticles that act on both and cause destruction of DNA [96]. Table 4 and 5 exhibit silver nanoparticles and their combination with other nanoparticles used for the management of fungal plant pathogens.

Management of viral diseases

There were three metal nanoparticles include Ag, Au and zinc used to control the viruses; an anthropological study showed that silver nanoparticles were used effectively against human viruses such as Tacaribe virus [97] and influenza virus [87] 98], similar nanoparticles (Ag and Zn)have also been used against plant viruses for instance, Bean yellow mosaic virus [99], Potato virus Y [100], Sunhemp rosette virus [101] and Cucumber mosaic virus [102].

Mode of action: Elbeshehy and his co-workers experimented that silver nanoparticles bind with virus envelopes inhibit virus infection [99] and similar results exhibit in table 6.

Used as preservatives

Recently, a pesticide product (NSPW-L30SS) containing nano-silver has been conditionally registered as preservative under FIFRA [103]. Silver nanoparticles are also used as preservatives because silver inhibits ethylene mediated processes, such as flowers abscission and senescence [104, 105]. Silver is also used in the packing industry to increase the shelf life of food products [106, 107].

Phytotoxicity of Nanoparticles

Silver is the second most poisonous element next to mercury to all the living beings in an ecosystem [108]. Silver nanoparticles leach silver ions (Ag^+) which are bio-accumulative, persistent and highly toxic to organisms [109], therefore, the release of AgNPs into ecosystems raise great concerns about their safety and environmental toxicity [110]. As a result, the release of AgNPs into habitats poses serious questions about their safety and toxicity to the environment [111].

Though silver and silica control powdery mildew pathogens but its higher concentration i.e., 3200 ppm causes phytotoxicity in plants [112]. Higher concentrations of AgNPs i.e., 5 to 20 mg/L resulted in a reduction of biomass in *Arabidopsis* [113]. Silver Nanoparticles with higher concentration shortened the length of wheat shoots and roots [114], reduced root elongation, shoot and root fresh weight in rice [115], inhibited seed germination and decreased biomass in zucchini (*Cucurbita pepo*) [116, 117]. In lettuce crop 1 and 2 mg/mL concentration of Al_2O_3 decreased biomass 10.4 and 17.9 percent respectively while 0.4 and 1 mg/mL concentration of $AlCl_3$ found reducing biomass 22.3 and 9.96 percent respectively [118]. Zinc oxide (ZnO) as nanoparticle was investigated for its toxicity, in this study root uptake and Phytotoxicity were observed by TEM and SEM and found that in the presence of ZnO nanoparticles *Lolium perenne* biomass reduced significantly, root tips shrink and cortical & epidermal cells of roots vacuolated and collapsed severely [118]. Similar results of Phytotoxicity were reported in *Cucumis sativus* and *Fagopyrum esculentum* in 2012 and 2013 respectively by Kim et al. [119, 120].

Conclusion

Use of nanoparticles in India still is in the research phase and has been proved to be very useful in the agriculture sector in the near future [121]. The active compounds of nanoparticles are supposed to be used as nano-fungicides, nano-insecticides, nano-bactericides, nano-weedicides, nano-virucides etc. effectively and extensively in the days to come [122]. Nano particles seem to be eco-friendly as they possess low residual effect and will be used as antimicrobial compounds against microorganisms which are used to develop pesticide resistance against synthetic pesticides [123]. Wide range application of nanoparticles makes it futuristic in many senses as nanoparticles used not only as pesticides but as growth regulators to accelerate balanced growth into roots and shoots contributing good yield, as fertilizers to fulfill the nutritional requirement of the plant, as gene regulators in genetics for the settling of desired genes among the plant species, as bio primer used in coating seeds, medicines, food materials to enhance their properties and to protect from outer threats. Nanoparticles are also had great ability to be used as food preservatives to improve self-life of the product and value addition. More research using nanotechnology and nanoparticles are required to prove and rehears previously done research worldwide.

Table 6: Silver nanoparticles against viral plant pathogens.

Virus	Plant	Reference
Banana bunchy top virus	Banana	[101]
Sunhemp rosette virus (SHRV)	*Cymopsis tetragonaloba*	[157]
Bean yellow mosaic virus (BYMV)	*Vicia faba*	[92]
Tobacco mosaic virus (TMV)	*Nicotiana tabacum*	[86]
Potato virus Y (PVY)	*Solanum tuberosum*	[158]
Tomato spotted wilt virus (TSWV)	*Solanum tuberosum* L. cv. Spunta	[159]
Tomato mosaic virus (ToMV)	*Solanum lycopersicum*	[160]
Potato virus Y (PVY)	*Solanum lycopersicum*	[160]
Cucumber mosaic virus (CMV)	*Cucumis sativus*	[102]

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