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REVIEW ARTICLE

Biosynthesis of nanoparticles using eco-friendly factories and their role in plant pathogenicity: a review

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Abstract Nanoparticles (NPs) have been synthesized by various methods like physical, chemical and biological methods. Physical and chemical methods are costly and toxic to the environment. So there is an emerging need for production of nanoparticles using nontoxic, eco-friendly and reliable methods to expand their applications in agriculture field. Best option to achieve this goal is the use of biological entities such as microorganisms and plant extracts to synthesize nanoparticles. The main focus of this review is to compile the studies of synthesis of nanoparticles using ''eco-friendly nano-factories'' i.e., plant extract and microorganisms. Agriculture is an area where new technologies are often applied to improve the yield of crops. Plant diseases are one of the major factors that affect crop productivity. The problem with disease management lies with the detection of the exact stage of prevention. The employment of nanoparticles in agriculture field with some beneficial effects to the crops will be promising step toward nano-revolution in agriculture field. This review also summarizes antimicrobial activity of nanoparticles, their influence on the plant growth parameters and their role in plant pathogenicity.

Introduction

Nanotechnology is the fascinating area of research in the field of material science, medical science, life science, physical & chemical sciences. Today, metal nanoparticles have drawn the attention of scientists due to their extensive application in the development of new technologies in different areas (Lv, Zhang, Zeng, & Tang, 2018; Qiu, Shu, & Tang, 2018; Shu, Qiu, Lv, Zhang, & Tang, 2018; Zhang, Lv, Lin, Li, & Tang, 2018; Zhou, Lin, Zhang, & Tang, 2018). It is estimated that the global market for nanoparticles in biotechnology and pharmaceuticals will be expected to reach nearly $79.8 billion in 2019, with a compound annual growth rate (CAGR) of 22.0% for the period of 2014–2019 (BBC Research, 2014). In recent years, physical methods

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have gained much interest for the production of thin films as well as nanoparticles (NPs) and their aggregates (Ullmann, Friedlander, & Schmidt-Ott, 2002). Environment toxicity is the major concern with physical and chemical synthesis methods. Thus, there is an emerging need for alternative sources for the synthesis of nanoparticles; recently scientists have been reported many microorganisms as possible eco-friendly nanofactories (Bansal, Kaur, Kumar, Surekha, & Duhan, 2017; Deepika, Jacob, Mallikarjuna, & Verma, 2013; Kaur, Jain, Kumar, & Thakur, 2014). More recently, copper nanoparticles (NPs) were biosynthesized with the peel extract of pomegranate (Kaur, Thakur, & Chaudhury, 2016). A simple and efficient biosynthesis method has been reported to prepare easily harvested biocompatible cadmium telluride (CdTe) quantum dots (QDs) with tunable fluorescence emission using yeast cells (Bao et al., 2010).

Role of nanoparticles in agriculture is known as nano-agriculture i.e. new technology is often applied to improve the yield of crops (Duhan et al., 2017). Nanoparticles synthesized from different biological sources can be applied in agriculture (Kaur, Thakur, Duhan, & Chaudhury, 2018). TiO_2 NPs have been found to induce seed germination in spinach and plant growth by regulating the germination of aged seeds and its vigor (Zheng, Hong, Lu, & Liu, 2005). Metal nanoparticles can be consumed by plants in the form of micronutrient; but it is not avoidable that high dose of nanoparticles in soil cause pollution (Rajput et al., 2018). So, there is a need to minimize the dose of metal nanoparticles in the soil. Embedding of these metal nanoparticles in biocompatible polymers is better alternative to minimize the dose with high efficacy (Kaur, Duhan, Thakur, & Chaudhury, 2018). Kaur, Duhan, et al. (2018) used chitosan as polymer and synthesized chitosan-metal nanocomposites which have excellent antifungal activity against Fusarium wilt and showed positive effect on plant growth parameters of chickpea. Here, main emphasis of this review is the collection of studies based on biosynthesis of nanoparticles using eco-friendly sources like microorganisms and plants and concluded that the use of nanoparticles in agriculture field may offer a highly effective novel platform for management of the different diseases of crops.

Biosynthesis of nanoparticles

There are a large number of physical, chemical, biological, and hybrid methods available to synthesize different types of nanoparticles (Diallo et al., 2017; Liu et al., 2010; Sone, Diallo, Fuku, Gurib-Fakim, & Maaza, 2017). Although physical and chemical methods are popular for synthesis of nanoparticles but the use of toxic chemicals greatly limits their biomedical applications, particularly in clinical fields (Mafune, Kohno, Takeda, & Kondow, 2001). Nature has devised various processes for the biosynthesis of nanomaterials, an unexplored area of research (Bansal, Duhan, & Gahlawat, 2014). The synthesis and assembly of nanoparticles by biological routes may lead to the development of clean, nontoxic and environmentally acceptable ''green chemistry'' procedures, probably involving organisms ranging from bacteria to fungi and even plants (Konishi et al., 2007). The three main steps, involved in the preparation of nanoparticles that should be evaluated from a green chemistry perspective, are the choice of the solvent medium used for the synthesis, an environmentally benign reducing agent and a nontoxic material for the stabilization of the nanoparticles. Most of the synthetic methods reported to date rely heavily on organic solvents which cause an adverse effect in the environment and not safe to human beings (Parashar, Parashar, Sharma, & Pandey, 2009). Thus, research need to be shifted toward the use of eco-friendly and biocompatible methods for the synthesis of nanoparticles as they are safe for agriculture applications. So, microorganisms and plant extracts as a source of nanoparticles synthesis could be used as eco-friendly nano-factories (Fig. 1).

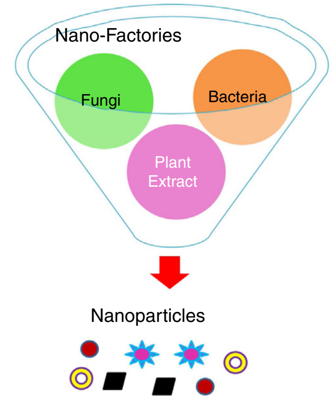

Figure 1 Biosynthesis of nanoparticles using ''ecofriendly nano-factories''.

Bacteria as nano-factories for the synthesis of nanoparticles

Many organisms have been reported to produce inorganic materials either intracellularly or extracellularly. Among the microorganisms, prokaryotic bacteria have received the most attention in the area of metal nanoparticles biosynthesis. The formation of extracellular and intracellular metal nanoparticles by bacteria like *Escherichia coli*, *Pseudomonas stutzeri*, *Pseudomonas aeruginosa*, *Plectonema boryanum*, *Salmonella typhus*, *Staphylococcus currens*, *Vibrio cholerae*, etc., have been reported (Klaus, Joerger, Olsson, & Granqvist, 1999; Konishi, Nomura, Tsukiyama, & Saitoh, 2004). Silver nanoparticles with an average particle size of around 50 nm, were synthesized by bacteria *Bacillus licheniformis*, isolated from sewage collected from municipal wastes (Kalimuthu, Babu, Venkataraman, Bilal, & Gurunathan, 2008). Recently, a rapid method for synthesizing small (1–7 nm) monodisperse AgNPs has been described by electrochemically active biofilm (EAB) using sodium acetate as an electron donor (Kalathil, Lee, & Cho, 2011). The hypothetical mechanism for the synthesis of nanoparticles was found that nitrate reductase; an enzyme present in nitrogen cycle is responsible for the reduction of metal ions in NPs (Duran, Marcato, Alves, De Souza, & Esposito, 2005).

Earlier studies have been found that environmentally and ecologically important bacteria are also responsible for biosynthesis of gold nanoparticles (GNPs). *Rhodopseudomonas capsulata* (He et al., 2007), *E. coli* (Du, Jiang, Liu, & Wang, 2007), *Klebsiella pneumoniae* (Srinath & Rai, 2014), *Arthrobacter nitroguajacolicus* (Dehnad, Hamedi, Derakhshan-Khadivi, & Abusov, 2015) and *Brevibacillus formosus* (Srinath, Namratha, & Byrappa, 2017) were investigated for reducing Au^{3+} ions at room temperature with a single step process. The exact mechanism for synthesis of gold nanoparticles, yet to be illustrated but some scientists reported the involvement of electron shuttle enzymatic metal reduction process (Mukherjee et al., 2002; He et al., 2007). The bioreduction of Au^{3+} to Au^{0} by bacteria for biosynthesis of gold nanoparticles indicated the involvement of NADH- and NADH dependent enzymes. Table 1 shows selected examples of the bacterial-mediated synthesis of metal nanoparticles.

Biosynthesis of nanoparticles by fungi

Myconanotechnology is a new term that is defined as the fabrication of nanoparticles by fungi and their subsequent application, particularly in medicine (Rai, Yadav, & Gade, 2009). Fungi have a number of advantages for nanoparticle synthesis compared with other microorganisms, as they are relatively easy to isolate, downstream processing is much simple as compared to bacterial fermentations and culture secrete large amounts of extracellular enzymes, and have wide range and diversity.

The mycosynthesis of silver nanoparticles using 1 mM silver nitrate ($AgNO_3$) solution as a precursor with the culture supernatants of the fungus *Aspergillus terreus* (Bansal, Kaur, & Duhan, 2017), *Fusarium acuminatum* isolated from infected ginger (*Zingiber officinale*) (Ingle, Gade, Pieratt, & Honnichesen, 2008) and *Fusarium pallidoroseum* (Bansal, Kaur, & Duhan, 2017) have been evaluated and silver nanoparticles were formed within minute of silver ion coming in contact with the cell.

Gold nanoparticles (AuNPs) have been reported as a widespread research tool in various fields of the health center, medicine and agriculture due to their biocompatibility and stability. Fungi mediated methods for the synthesis of gold nanoparticles suggested the two main precursors $HAuCl_4$ and AuCl which dissociates to Au^{3+} ions and Au^{+}, respectively (Kitching, Ramani, & Marsili, 2015). Endophytic fungus *Aspergillus clavatus*, isolated from surface sterilized stem tissues of *Azadirachta indica*. A. Juss., when incubated with an aqueous solution of chloroaurate ions produced a diverse mixture of intracellular gold nanoparticles (Au NPs), especially nanotriangles (GNT) in the size range from 20

Table 1 Metal nanoparticles synthesized by bacteria.

Bacteria	Nanoparticles produced	Size(nm)	Extracellular/Intracellular	References
Bacillus cereus	Ag	4–5	Intracellular	Babu and Gunasekaran (2009)
Bacillus licheniformis	Ag	50	Extracellular	Kalimuthu et al. (2008)
Brevibacterium casei	PHB	100–125	Intracellular	Pandian et al. (2009)
Brevibacterium casei	Au, Ag	10–50	Intracellular	Kalishwaralal, Deepak, Ram, and Pandian (2010)
Corynebacterium glutamicum	Ag	5–50	Extracellular	Sneha, Sathishkumar, Mao, Kwak, and Yun (2010)
Corynebacterium sp.	Ag	10–15	–	Zhang et al. (2005)
Desulfobacteraceae sp.	CdS	2–5	Intracellular	Labrenz, Druschel, and Thomsen-Ebert (2000)
Enterobacter sp.	Hg	2–5	Intracellular	Sinha and Khare (2011)
Escherichia coli	Au	20–30	Extracellular	Du et al. (2007)
Escherichia coli	Ag	50	Extracellular	Gurunathan, Kalishwaralal, and Vaidyanathan (2009)
Escherichia coli	CdTe	2.0–3.2	Extracellular	Bao et al. (2010)
Geobacter sulfurreducens	Ag	10–200	–	Law, Ansari, Livens, Renshaw, and Lloyd (2008)
Lactic acid bacteria	Ag	11 ± 2	–	Sintubin et al. (2009)
Lactobacillus sp.	$BaTiO_3$	20–80	Extracellular	Jha and Prasad (2010)
Morganella sp.	Ag	20 ± 5	–	Parikh et al. (2008)
Proteus mirabilis	Ag	10–20	–	Samadi et al. (2009)
Pseudomonas aeruginosa	Au	15–30	Extracellular	Husseiny, Aziz, Badr, and Mahmoud (2007)
Rhodobacter sphaeroides	ZnS	10.5 ± 0.15	Extracellular	Bai, Zhang, and Gong (2006)
Staphylococcus aureus	Ag	1–100	–	Nanda and Saravanan (2009)
Ureibacillus thermosphaericus	Au	50–70	Extracellular	Juibari, Abbasalizadeh, Jouzani, and Noruzi (2011)
Salmonella enterica	Au	42	–	Mortazavi, Khatami, & Sharifi (2017)
Silver resistance bacteria	Ag	<100 nm	–	Agrawal, Nikhilesh, and Kulkarni (2017)

to 35 nm (Verma, Kharwar, & Gange, 2010). Extracellular production of gold, silver (Duran et al., 2005) and bimetallic Au–Ag alloy nanoparticles (Mukherjee et al., 2002), CdS nanoparticles (Ahmad et al., 2003) and zirconia nanoparticles (Bansal, Rautaray, Ahmad, & Sastry, 2004) by the fungus *Fusarium oxysporum* was already reported. Other fungi have been also responsible for the synthesis of metal nanoparticles like iron nanoparticles (Saif, Tahir, & Chen, 2016), bimetallic nanoparticles (Castro-Longoria, Vilchis-Nestor, & Avalos-Borja, 2011) and PbS nanocrystals (Kaur et al., 2014). In addition, nanoparticles of high monodispersity and dimensions can be obtained from fungi (Mukherjee et al., 2001). Mainly, proteins secreted by fungi could be capable of hydrolyzing metal ions quickly and through non-hazardous processes. This review summarized the selected examples of metal nanoparticles synthesized by fungi in Table 2.

Biosynthesis of nanoparticles by plant extract

Plant-mediated biosynthesis is very easy and cost-effective method for production of nanoparticles. There is a problem in maintaining and preserving a microbial cultures due to contamination. Plants for this purpose could be used to avoid the time consuming steps of maintaining and preservation of cell cultures. Plant-mediated biosynthesis is a simple and suitable method for large-scale production of nanoparticles without any contamination (Kaur et al., 2016). A number of plants have been reported for biosynthesis of nanoparticles (Ismail, Khenfouch, Dhlamini, Dube, & Maaza, 2017; Khalil et al., 2017; Matinise, Kaviyarasu, Mongwaketsi, Khamlich, & Maaza, 2018)

Leaves are the food factories of plants, so this is inspiration step for researcher and scientists to use leaves as nanofactories for production of silver nanoparticles. Many reports are available in which leaf extract have been used for production of silver nanoparticles due to easy and simple experimental design like leaf broth of *Azadirachta indica* (Shankar, Rai, Ahmad, & Sastry, 2004), phyllanthin extract (Kasthuri, Kathiravan, & Rajendiran, 2009), *Mentha piperita* (Parashar et al., 2009), *Ocimum sanctum* (Mallikarjuna et al., 2011). Other parts of plants as an extract for the synthesis of silver nanoparticles have been also studied e.g. ethanolic extract of Marigold flower (Kaur, Thakur, Kumar, & Dilbaghi, 2011) and kinnow extract (Bansal, Kaur, Surekha, Kumar, & Duhan, 2017).

Gold nanoparticles with average size of 32.96 ± 5.25 nm were synthesized using *Garcinia mangostana* commonly known as mangosteen fruit peel (Lee, Kamyar, Miyake, & Yew, 2016). Biosynthesis of copper nanoparticles, gold-iron and silver iron core–shell nanoparticles using extracts of *Punica granatum* was also reported (Kaur, Malwal, Thakur, Manuja, & Chaudhury, 2018; Kaur et al., 2016) and characterized using UV-Visible spectroscopy, Fourier transform infra red spectrophotometer (FTIR) and TEM. Synthesis of nanoparticles was confirmed by UV-visible spectrophotometer, X-ray diffraction (XRD) and scanning electron microscope (SEM). Their observation through particle size analyzer (PSA) and transmission electron microscope (TEM) showed dominant spherical morphology with an average diameter of 5 nm (Bansal et al., 2017b). Table 3 denotes the application of selected plants extracts for the synthesis of nanoparticles.

Table 2 Metal nanoparticles synthesized by fungi.

Fungi	Nanoparticles produced	Size (nm)	Extracellular/intracellular	References
Aspergillus clavatus	Ag	10–25	Extracellular	Verma, Kharwar, and Gange (2010)
Aspergillus flavus	Ag	8.92 ± 1.62	Intracellular	Vigneshwaran et al. (2007)
Aspergillus fumigatus	Ag	5–25	Extracellular	Bhainsa and D'Souza (2006)
Aspergillus flavus	Ag	20	Extracellular	Gade et al. (2008)
Cladosporium cladosporioides	Ag	10–100	Extracellular	Balaji et al. (2009)
Fusarium oxysporum	Silica and titanium particles	5–15	Extracellular	Bansal, Ramanathan, and Kumar (2005)
Fusarium oxysporum	CdSe quantum dots	–	Extracellular	Kumar, Ayoobul, Absar, and Khan (2007)
F. oxysporum and *Verticillium* sp.	Magnetite	20–50	Extracellular	Bharde et al. (2006)
Fusarium semitectum	Ag	10–60	Extracellular	Basavaraja, Balaji, Lagashetty, Rajasab, and Venkataraman (2007)
Penicillium brevicompactum	Ag	23–105	Intracellular	Shaligram et al. (2009)
Penicillium fellutanum	Ag	1–100	Extracellular	Kathiresan, Manivannan, Nabeel, and Dhivya (2009)
Phaenerochaete chrysosporium	Ag	–	Extracellular	Vigneshwaran et al. (2007)
Agpergillus sp.	PbS	10–15	Extracellular	Kaur et al. (2014)
Aspergillus niger	Ag	40–45	Extracellular and intracellular	Bansal, Kaur, Kumar, et al. (2017)

Table 3 Metal nanoparticles synthesized by plants.

Plants	Nanoparticles produced	Size (nm)	Extra/intracellular	References
Acanthella elongate	Au	7–20	Extracellular	Inbakandan, Venkatesan, and Ajmal Khan (2010)
Alfalfa	Ti/Ni bimetallic	1–4	–	Schabes-Retchkiman et al. (2006)
Aloe vera	Ag	15.2 ± 4.2	Extracellular	Chandran, Chaudhary, Pasricha, Ahmad, and Sastry (2006)
Avena sativa	Au	5–20	Intracellular	Armendariz et al. (2004)
Azadirachta indica	Ag, Au and Ag/Au bimetallic	50–100	Extracellular	Shankar et al. (2004)
Black tea leaf	Ag/Au	–	–	Begum, Mondal, Basu, Laskar, and Mandal (2009)
Capsicum annum	Ag	10–40	Extracellular	Li et al. (2012)
Carica papaya	Ag	60–80	Extracellular	Mude, Ingle, Gade, and Rai (2009)
Cinnamomum camphora Leaf	Ag	5–40	–	Huang et al. (2008)
Coriandrum sativum leaf extract	Ag	–	Extracellular	Sathyavathi, Krishna, Rao, Saritha, and Rao (2010)
Jatropha curcas	Ag	10–20	–	Bar et al. (2009)
Sesuvium portulacastrum	Ag	5–20	–	Nabikhan, Kandasamy, Raj, and Alikunhi (2010)
Ethanolic extract of Marigold flower	Ag	5	Extracellular	Kaur et al. (2011)
Rosmarinus officinalis	Ag	5–10	–	Sulaiman, Mohammad, Abdul-wahed, and Ismail (2013)
Aspalatus linearis	NiO	100 nm	–	Diallo, Manikandan, Rajendran, and Maaza (2016)
Hibiscus sabdariffa	CeO NPs	3.9 nm	–	Thovhogi, Diallo, Gurib-Fakim, & Maaza (2015)
Garcinia mangostana	Gold NPs	32.96 ± 5.25	–	Lee et al. (2016)
Moringa oleifera	ZnO NPs	15–20	–	Matinise, Fuku, Kaviyarasu, Mayedwa, and Maaza (2017)
Moringa oleifera	NiO	305.46 nm and 410 nm	–	Ezhilarasi et al. (2016)
Callistemon viminalis	$BiVo_3$	–	–	Mohamed, Sone, Dhlamini, and Maaza (2018)

Nanoparticles as antimicrobials

The emergence of nanoscience and nanotechnology in the last decade presents opportunities for exploring the bactericidal effect of metal nanoparticles. The bactericidal effect of metal nanoparticles has been attributed to their small size and high surface to volume ratio, which allows them to interact closely with microbial membranes and is not merely due to the release of metal ions in solution (Kaur, Thakur, & Chaudhary, 2011). The antimicrobial properties of ZnO and gold nanoparticles against *E. coli* and *Staphylococcus aureus* (Kaur, Thakur, et al., 2011; Srinath et al., 2017), silver nanoparticles and copper nanoparticles against *S. aureus*, *P. aeruginosa* and *Salmonella entrica* (Kaur, Thakur, & Chaudhary, 2013;Kaur et al., 2015), GNPs against *E. coli* and *Salmonella typhi* (Lima, Guerra, Lara, & Guzman, 2013) and insoluble cross-linked quaternary ammonium polyethylenimine (PEI) nanoparticles against *S. aureus*, *Staphylococcus epidermidis*, *Enterococcus faecalis*, *P. aeruginosa* and *E. coli* (Beyth et al., 2008) were well-established. Several mechanisms for their bactericidal effects have been proposed that have been increasingly studied for their antibacterial properties and potential applications in food, the environment, and healthcare.

Metal nanoparticles may be combined with polymers to form composites for better utilization of their antimicrobial activity. Kaur, Thakur, and Chaudhury (2012) reported the antibacterial and antifungal activity of silver-chitosan nanoformulations against *S. aureus*, *P. aeruginosa* and *S. entrica and* plant pathogens i.e. *Rhizoctonia solani*,

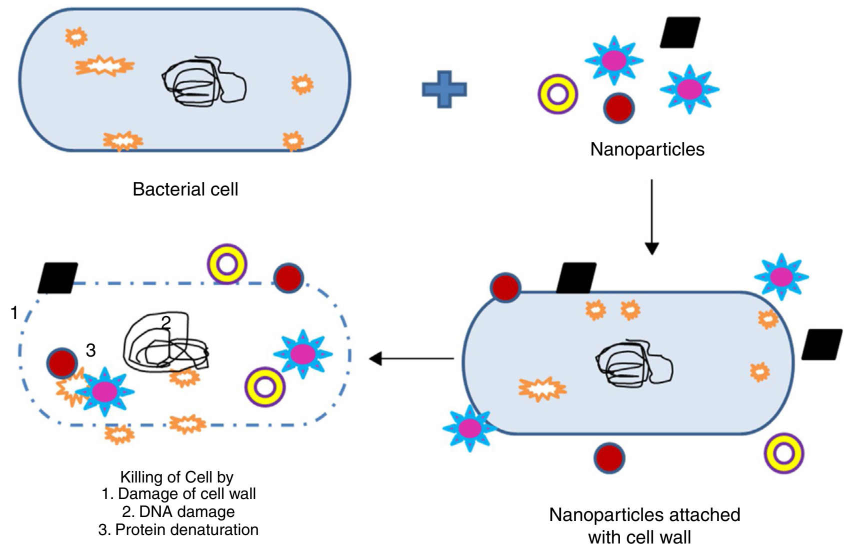

Figure 2 Hypothetical antimicrobial mechanism of nanoparticles against bacterial cell.

Aspergillus flavus, *Alternaria alterneta*, isolated from seeds of chickpea, respectively. Though there are many mechanisms attributed to the antimicrobial activity shown by nanoparticles, mainly DNA damage and cell wall disruption are the most common cause of cell death (Kaur, Thakur, et al., 2011; Dakal, Kumar, Majumdar, & Yadav, 2016). Nanoparticles get to adhere to the cell wall and cell membrane due to electrostatic interactions and disrupt the cell wall which causes leakage of macromolecules or maybe a pass through the cell membrane and damage DNA of cells which cause cell death as shown in Fig. 2.

Nanoparticles in plant pathogenicity

The use of nano-sized particles as agrochemicals has become more common as technological advances make their production more economical for agriculture applications. Primary requirements for the potential use of nanoparticles in plant disease control include more information about the antimicrobial activity of various nano size compounds against phytopathogens and the development of better application strategies to increase the efficacy of disease suppression. Silver nanoparticles have been reported as very effective against two plant-pathogenic fungi, *Bipolaris sorokiniana* and *Magnaporthe grisea* in vitro (Jo, Kim, & Jung, 2009), *Erwinia carotovora* pv. *carotovora* and *Alternaria solani* (Abbas, Naz, & Syed, 2015) and *Phytophthora* blight and *Alternaria* blight (Zakharova, Gusev, & Zherebin, 2017). Ismail, Sidkey, Arafa, Rasha, & El-Bata (2016) evaluated the combine effect of silver and selenium nanoparticles against *A. solani*, the pathogenic fungus causing early blight disease of potato. The fungus isolated from leaf spot was identified using microscopic and treated fungal hyphae showed the formation of pits and pores. Thus, it can be concluded that the mycosynthesized AgNPs were able to pass and distribute throughout the fungal cell area and interact with the cell components and cause cell death.

Copper−chitosan (Cu/Ch) nanoformulations have been prepared for antifungal activity against *A. solani* causing agent of early blight tomato (*Solanum lopersicum* Mill). These nanoparticles caused inhibition of mycelial growth as well as spore germination in *A. solani* and *F. oxysporum*, respectively, in an in vitro model (Saharan et al., 2015). Another work reported on silver/chitosan nanoformulations (NFs) against various seed borne plant pathogens, especially seed borne disease-causing fungi, isolated from chickpea seeds (Kaur et al., 2012). These studies reveal the possibility of nanoparticles as an alternative to fungicides for controlling phytopathogens.

ZnO nanoparticles have been recently investigated as effective fungicides against phytopathogens. ZnO nanoparticles have advantages over silver nanoparticles for fungal pathogen control efforts (Dimkpa, McLean, Britt, & Anderson, 2013). He et al. (2011) evaluated antifungal activities of zinc oxide nanoparticles (ZnO NPs) and their mode of action against two postharvest pathogenic fungi (*Botrytis cinerea* and *Penicillium expansum*). Application of different concentration of NPs on fungal hyphae was reported to damage cell wall and collapse fungal hyphae. The antibacterial potential of photocatalytic nanoscale titanium dioxide (TiO_2), nanoscale TiO_2 doped (incorporation of other materials into the structure of TiO_2) with silver (TiO_2/Ag), and nanoscale TiO_2 doped with zinc (TiO_2/Zn; Agri-Titan) has been evaluated against *Xanthomonas perforans*, the causal agent for bacterial spot disease of tomato (Paret, Vallad, Averett, Jones, & Olson, 2013). The synthesis and characterization of mesoporous alumina sphere (MAS) nanoparticles to evaluate their biological activity against tomato root rot caused by *Fusarium oxysporium*, as compared with the recommended fungicide, tolclofos-methyl, under laboratory and greenhouse conditions have been reported by Shenashen, Derbalah, Hamza, Mohamed, and Safty (2017). The authors reported cell death due to the entry of nanoparticles in bacterial cells due to disruption of the cell membrane and malformation of hyphal in the fungal cell.

Effect of nanoformulations on plant growth parameters

Effect of nanoparticles on crop plants is an emerging area of research that needs to be meticulously explored. In the recent past, engineered nanoparticles have received particular attention as potential candidates for improving crop yield (Barik, Sahu, & Swain, 2008; Scrinis & Lyons, 2007). Nanoparticles have mainly been targeted for controlled release of agrochemicals and site-targeted delivery of various macromolecules needed for improved plant disease resistance, efficient nutrient utilization and enhanced growth (Nair et al., 2010). Scientists have reported contrasting results with the use of nanoparticles on plant growth. Roghayyeh, Mehdi, and Rauf (2010) have also reported an increase in pod weight, leaf and pod dry weight and yield of soybean, on treatment with nano-iron. However, the growth of *Sesbania* seedlings in gold solution did not show any remarkable difference between control and treated seedlings, even up to 200 ppm gold concentration. Musante and White (2010) have reported a decline in growth of *Cucurbita pepo*, on treatment with silver and copper nanoparticles. Miao, Quigg, Schwehr, Xu, & Santschi (2007) have also reported that silver nanoparticles exert a negative effect on the growth of phytoplankton. Further, limited information is available on the mode of action of these nanoparticles on crop plants. Metal nanoparticles present more surface area for valance electron exchange with biomolecules, due to their higher surface area to volume ratio (Shah & Belozerova, 2009). Therefore, use of metal nanoparticles can alter the antioxidant status of the treated plants, by virtue of their ability to participate in cellular redox reactions.

All nanoparticles tested in the study influenced the growth of lettuce seeds as measured through shoot/root ratios of the germinated plant ($P < 0.05$). Phytotoxicity is an important consideration to understand the potential environmental impacts of manufactured nanomaterials. The effects of four metal oxide nanoparticles, aluminum oxide, silicon dioxide, magnetite, and zinc oxide, on the development of *Arabidopsis thaliana* (Mouse-ear cress), has been reported by Lee et al. (2010). ZnO NPs increased the level of IAA in roots (sprouts) when applied to *Cicer arietinum* seeds, which in turn indicate the increase in the growth rate of plants as zinc is an essential nutrient for plants (Pandey, Sanjay, & Yadav, 2010). The positive impact of zinc oxide nanoparticles on roots of rice *O. sativa* L. have been evaluated by Boonyanitipong, Kumar, Kositsup, Baruah, and Dutta (2011). Dhoke, Mahajan, Kamble, and Khanna (2013) reported the interactions of zinc oxide (nano-ZnO), iron oxide (nanoFeO) and the combination of these oxides with Cu (nano-ZnCuFe-oxide) with *Vigna radiate* and their role as micronutrients. The effect of IOMNPs (Fe_3O_4 and γ-Fe_2O_3) on the soil bacterial community with molecular approaches and enzyme analyses has been investigated by He et al. (2011). Impact of silver nanoparticles on crops like barley (Gruyer, 2014), wheat (Jhanzab et al., 2015), *Brassica* (Pallavi, Srivastava, Arora, & Sharma, 2016) and radish (Zuverza-Mena, Armendariz, Peralta-Videa, & Gardea-Torresdey, 2016) has been reported and no significant negative impact of NPs was found on any plant species. Arora et al. (2012) have been reported the positive effect of gold nanoparticles on various growth and yield-related parameters, including plant height, stem diameter, number of branches, number of pods, seed yield, etc. Therefore, implementation of nanoparticles in agriculture could be beneficial to increase the growth and yield of crops followed by suppression of phytopathogen.

Conclusions

Biosynthesized nanoparticles could be used effectively against plant phytopathogen to protect the various crop plants and their products, instead of using the commercially available synthetic pesticides, which show higher toxicity to humans. Thus, it can be said that all the nanoparticles have no significant negative impact on seed germination, root-shoot ratio, and soil microflora while some are beneficial to the plants and in turn to the farmer. There are myriad of nanomaterials including polymeric nanoparticles, iron oxide nanoparticles, gold nanoparticles and a silver ion which can be easily synthesized and exploited as a pesticide. Finally, we can conclude that nanobiotechnology is an important area of research that deserves all our attention owing to its potential application to agriculture.

Future prospects

There has been significant interest in using nanoparticles against the phytopathogens to promote agriculture. Use of nanoparticles for delivery of antimicrobials or drug molecules will be at its helm in near future for therapy of all pathological sufferings of plants. The eventual fate of utilizing nanoparticles as a fungicide to other crops appears extremely promising.

It is necessary to conduct further investigation to explore the phytotoxic action of nanoparticles and their take-up by plants as micronutrients and long-haul impacts of nanoparticles at the molecular level in crops.

While these issues are being tended to, future research should be targeted on working to better comprehend the interaction between the different forms of micronutrient nanoparticles, the plant, and the wide array of plant pathogens that assault them.

Conflicts of interest

The authors declare no conflicts of interest.

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