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Review Article

Green nanotechnology for plant bacterial diseases management in cereal crops: a review on metal-based nanoparticles

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Abstract

Cereals are an important source of nutrients for animals. Several diseases cause severe yield loss in cereal crops. Bacterial diseases result in varying yield losses across cereals: Wheat (5-40%), maize (15-98.9%), rice (20-70%), pearl millet (3-35%), and oats (15-49%). Diseases may be bacterial diseases, fungal or viral. Bacterial diseases are traditionally treated by pesticides. Chemically synthesized pesticides are toxic and hazardous to the environment. Nanotechnology is emerging and novel field for agriculture especially in plant pathology as a strong antimicrobial agent. Nanoparticles have been synthesized in various ways i.e., biological, physical and chemical methods. Chemical and physical methods of nanoparticles are costly and toxic to the environment. Biological method for the synthesis of nanoparticles is eco-friendly and economical. Microorganisms or plant extract are used for metal nanoparticle synthesis. The application of nanoparticles in agriculture has a wide

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scope and it can bring nano-revolution. This review summarizes the antibacterial activity of biosynthesized metal nanoparticles and their role in bacterial disease management of cereals.

Keywords: cereals; diseases; green technology; nanotechnology; plant pathology

Introduction

Cereal crops are the plants that belong to grass family Poaceae that are mainly grown for their edible grain. Cereals are economically important crops because they provide fundamental nutrition to majority of world population. Grains of cereals have starch in their endosperm due to which they form a staple part in human nutrition. However, cereals are also used for livestock nutrition and their capability of being stored for long time of period increase their utility (McKevith, 2004). The Food and Agriculture Organization (FAO) of the United Nations estimates that 2780 million tonnes of such cereal crops were produced in 2020 (Abbott, 2019; Fatima *et al.*, 2021). Approximately, 68% of total wheat production over the world is used by humans and 20% is used for fuel production, fiber and feed of livestock that play an important role food system transformation. Currently, one of the major issues of world is rapid increase in global population *(Weston et al.*, 2022). Due to this demand of food is also increased. To maintain the balance between food production and food demand, it is mandatory to minimize yield losses due to bacterial diseases in cereals. In order to meet the desired and disease-free yield, it is necessary to follow two intimately linked goals like mitigation and management of bacterial disease in cereals. The first is to increase crop yield, particularly that of cereal crops, which can be attained through various methods, for example selective breeding, genetic modification, as well as carefully controlled irrigation and fertilization systems. The second is to minimize crop losses caused by pests and diseases, which are conservatively estimated to cause yield loss between 20-35% (King *et al.*, 2017). One the major yield loss factor in cereals is bacterial diseases. Yield loss in wheat is 11- 29% (Tillman *et al.*, 1999), in maize 2-15% (Tillman *et al.*, 1999), in rice 25% (Yang *et al.*, 2006; Yasmin *et al.*, 2017).

In the past, bacterial diseases were managed by chemical methods. Although chemical plant protection methods have proven effective in the long term, they have disadvantages for the environment and human health. Chemical crop protection technology has two main disadvantages. Firstly, evolution of pest resistance and secondly, broad-spectrum pesticides also kill natural enemies of insects (Felsot and Rack, 2006). It is reported that 90 % of pesticides are lost after application (Ghormade *et al.*, 2011). So, there is need to adopt modern techniques for pesticide application that will be less harmful, coast efficient and have high performance in terms of antimicrobial efficacy (Thind and Payak, 1985). Nanoparticles are the best pesticide alternate (Verma *et al.*, 2011). Nanoparticles are synthesized by physical, chemical and biological methods. Although physical and chemical methods are traditional methods (Stephens *et al.*, 2020). These methods are costly. However, biological methods are advanced and emerging methods. In biological methods, metal substrate is reduced by plant extract or microbes instead of chemical reagent (Mughal and Hassan, 2022). Biosynthesis of nanoparticles is a bottom-up approach where oxidation/ reduction occurs by phytohormones of plant or metabolites of microbes(Singh *et al.*, 2018). The focus of this review is on the scope of biosynthesized nanoparticles for bacterial disease control in major cereal crops like wheat, rice, maize, barley, rye, oats and millets by direct and indirect approaches.

Bacterial diseases in cereals

Plant pathogens such as bacteria damage crops in a various way such as spotting leaves, wilting of leaves and blighting. Bacteria as pathogen attack photosynthetic tissues and cause infection that ultimately block conducting tissues. In contrast with viruses that grow inside the plant cells, bacteria grow in spaces between the cells but cannot invade them. Plant-pathogenic bacteria cause symptoms like cankers, scabs, soft rots, blights, spots, wilts, outgrowth and galls (Wally and Punja, 2010). Symptoms of bacterial diseases in cereal crops are similar to that caused by fungus. Plant pathogenic bacteria produce proteins which degenerate pectin, which binds plant cell wall and ultimately, the plant cell lost its shape. Meanwhile, some bacteria secret digestive enzymes in plant cells that lead to host cell death (Ortmann *et al.*, 2023). Even some bacteria have the ability to modify host cell and cause mutation. Among these cereal crops, rice is the most commonly cultivated crop that widely suffers stress due to bacteria. Bacterial blight disease is considered as deadly disease that damages cultivated rice crops on a large scale. While during the pandemic period crop loss due to bacterial blight increases by up to 75% that resulting in huge destruction (Yang *et al.*, 2006). Bacterial blight (BB) disease is commonly found in all rice growing areas and controlling this disease is considered the most important task among all rice breeders in Asia.

Breeders have been using conventional strategies for many years, but these are not as effective as genomic strategies. These breeders have identified the resistant gene *Xa-4* and incorporated into cultivated crops of rice. These breeding programs have been effective against bacterial blight disease in rice (Sanchez *et al.*, 2000). Bacteria enter in damaged plants via wounds that are caused by insects, pests and wind. In maize, bacteria usually grow in maize growing areas and damage them. While in maize, primary diseases caused by bacteria are bacterial stalk rotting, holcus leaf spotting and gross wilting (Kulimushi *et al.*, 2017). Bacterial wilting of maize has also been found to be the most common disease in maize crop. Agriculturists have been using hybridizing techniques to make the plant resistant to biotic stress for many years. Through hybridizing approaches, they have developed resistant crop plants and increased their productivity but still bacterial diseases are considered a major threat to crop yield (Zhao *et al.*, 2005). For many decades, farmers are using a broad range of insecticides to combat bacterial diseases. Among these bacterial diseases, bacterial pathogen such as *Xanthomonas campestris* is a common source of bacterial blight in barley. These bacteria grow on the upper surface of leaves during cold and wet weather conditions. This bacterial disease causes damage almost 10 to 15% annually (Brown, 2002). The leaf blighting of barley by bacteria can only be reduced by using seeds resistant to disease and by spraying insecticides during different intervals(Luan *et al.*, 2016). Breeders have managed these bacterial diseases by using conventional strategies such as crop rotation of grain crops to non-grain crops and transgenic disease-free seeds (Babu and Gunasekaran, 2009).

Traditional methods to control bacterial diseases

There are 100 species of phytopathogenic bacteria reported yet. Traditionally, phytopathogenic bacteria and their diseases were managed by synthetic pesticides in plants. Pesticides decrease bacterial infection. The use of pesticides has the following benefits, the: can be stored for the long term, ease of use and give significantly quick visible results. But on the other hand, they also have some disadvantages like pathogenic resistance, chemical pollution and shifting ecosystem balance towards instability. According to WHO, about 1000 pesticides are being used around the World, which have different toxicity levels to ensure food security. Many older economical pesticides, such as lindane and dichlorodiphenyltrichloroethane (DDT), remain in the soil and the environment for many years because of their sustainability(Mali *et al.*, 2023). But later on, countries that were the members of the Stockholm Convention (2001) banned these pesticides. The toxicity of these pesticides depends upon their function and dose of pesticide. Different pesticides have different toxicity levels in different concentrations (Khan *et al.*, 2022). Meanwhile, pesticides have various negative effect on the environment, given in Figure 1.

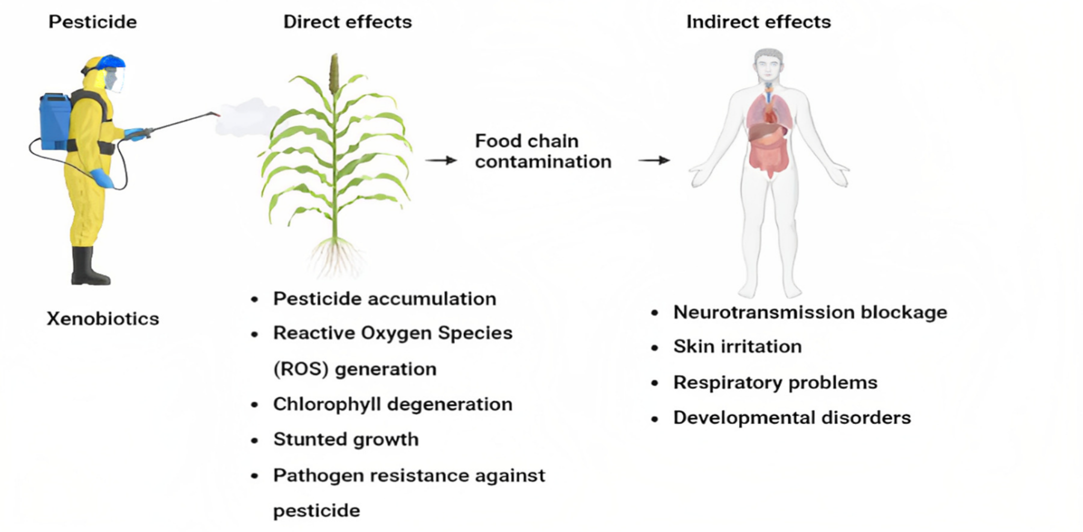

Figure 1. Direct and indirect impacts of pesticides on environment

Biosynthesis of nanoparticles

Various physical (Figure 2), chemical, and biological methods are currently used to synthesise different types of nanoparticles. Physical and chemical methods are quite famous for nanoparticle synthesis, but their applications are limited due to the use of toxic chemicals (Mewada *et al*., 2013). Nanoparticles synthesized by physical and chemical methods have a narrow threshold range in plants (Haidri *et al*., 2023). Toxicity is a major concern about physical and chemically synthesized nanoparticles (Shafqat *et al*., 2023a).

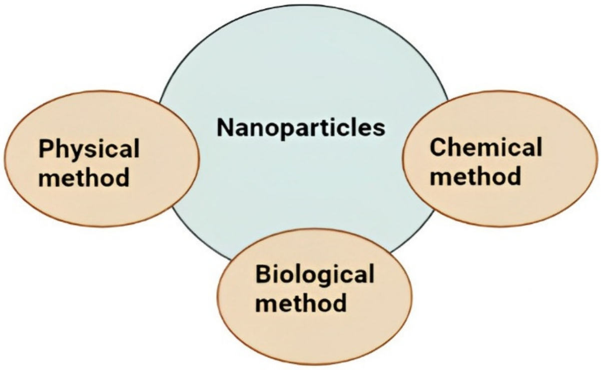

Figure 2. Methods of nanoparticle synthesis: exploring physical, chemical, and biological approaches

Biosynthesis of nanoparticles is explored by natural reducing agents, which are bacteria, fungi or plants (Pantidos, 2014; Tables 1,2,3). The synthesis and assembly of nanoparticles by this approach is termed "green chemistry," the resultant nanoparticles are nontoxic and ecofriendly (Rafique *et al*., 2016). Traditional physical and chemical rely greatly on organic solvents, which cause toxicity and have adverse effects on their applications to crops. In biosynthesis, a reducing agent or stabilizing agent is ecofriendly and nontoxic which may be a microorganism (Bacteria, fungi) or plant extract. The mechanism of biological synthesis of nanoparticles is elaborated in Figure 3, which explains biological metabolites as nano-reducing agents (Rafique *et al*., 2016). So, there is a need for research to be shifted towards biocompatible and eco-friendly methods of nanoparticles because they are safe for agriculture applications. For this purpose, plant extracts and microorganisms can be used as stabilizing agents for nanoparticle synthesis as an eco-friendly approach (Jain *et al*., 2011).

Table 1. Biosynthesis of nanoparticles by bacteria

Nano Particles	Bacterial Strains	Intra/Extra Cellular	Size (nm)	References
Ag	*Bacillus cereus*	Intracellular	4-5	(Babu and Gunasekaran, 2009)
Ag	*Bacillus licheniformis*	Extracellular	50	*(Shanthi et al., 2016; Tufail et al.*, 2022)
PHB	*Brevibacterium casei*	Intracellular	100-125	(Kiran *et al*., 2014)
Au, Ag	*Brevibacterium casei*	Intracellular	10-50	(Kalishwaralal *et al*., 2010)
Ag	*Corynebacterium glutamicum*	Extracellular	5-50	(Sneha *et al*., 2010)
Ag	*Corynebacterium sp.*	Extracellular	10-15	(Gowramma *et al*., 2014)
CDs	*Desulfobacteraceae sp.*	Intracellular	2-5	(Kucha *et al*., 2010)
Hg	*Enterobacter sp.*	Intracellular	2-5	(Sinha and Khare, 2011)
Au	*Escherichia coli*	Extracellular	20-30	(Du *et al*., 2007)
Ag	*Escherichia coli*	Extracellular	50	(Gurunathan *et al*., 2009)
CdTe	*Escherichia coli*	Extracellular	2.0-3.2	(Monrás *et al*., 2012)
Ag	*Geobacter sulfurreducens*	Extracellular	10-200	(Monrás *et al*., 2012; Thrall, 2012)
Ag	*Lactic acid bacteria*	Extracellular	11± 2	(Sintubin *et al*., 2009)
$BaTiO_3$	*Lactobacillus sp.*	Extracellular	20-80	(Jha and Prasad, 2010; Zhang *et al*., 2011)
Ag	*Morganella sp.*	Extracellular	20± 5	(Parikh *et al*., 2011)
Ag	*Proteus mirabilis*	Extracellular	10-20	(Parveen *et al*., 2018)
Au	*Pseudomonas aeruginosa*	Extracellular	15-30	(Ali *et al*., 2020)
ZnS	*Rhodobacter sphaeroides*	Extracellular	10.5 ± 0.15	(Gong *et al*., 2018)
Ag	*Staphylococcus aureus*	Extracellular	1-100	(Nanda and Saravanan, 2009)
Au	*Ureibacillus thermosphaericus*	Extracellular	50-70	(Juibari *et al*., 2011, 2015)
Au	*Salmonella anterica*	Extracellular	42	(Mortazavi *et al*., 2017)
Ag	*Cupriavidus sp.*	Extracellular	< 100 nm	(Ameen *et al*., 2020; Santos *et al*., 2022)

Bacteria as nano-stabilizing agent for nanoparticle synthesis

There are many microorganisms that have been reported to produce inorganic materials either extracellularly or intracellularly (Gangan *et al*., 2023). Amongst these organisms, bacteria (prokaryotes) attained more attention for the biosynthesis of metal nanoparticles because their isolation is quite easy as compared to algae and fungi (Yaashikaa *et al*., 2022). The biosynthesis of metal nanoparticles by extracellular or intracellular methods were reported by *Pseudomonas stutzeri, Pseudomonas aeruginosa, Escherichia coli, Plactonema boryanum, Asiatic cholera, Salmonella typhi, Staphylococcus currens* (Nabikhan *et al*., 2010). For example, silver nanoparticles were biosynthesized by *Bacillus licheniformis* isolated from sewage water collected from municipal waste, with average size of 50 nm.

Table 2. Biosynthesis of nanoparticles by fungi

Nano particles	Fungal strains	Intra/ Extra cellular	Size (nm)	References
Ag	*Aspergillus clavatus*	Extracellular	10-25	(Verma *et al.*, 2011)
Ag	*Aspergillus flavus*	Intracellular	8.92 ± 1.62	(Jain *et al.*, 2011)
Ag	*Aspergillus fumigatus*	Extracellular	5-25	(Kathiresan *et al.*, 2009)
Ag	*Aspergillus flavus*	Extracellular	20	(Balaji *et al.*, 2009)
Ag	*Cladosporium cladosporioides*	Extracellular	10-100	(Balaji *et al.*, 2009)
Silica and titanium	*Fusarium oxysporium*	Extracellular	5-15	(Ishida *et al.*, 2013)
CdSe quantum	*Fusarium oxysporium*	Extracellular	-	(Yamaguchi *et al.*, 2016)
Magnetite	*F. oxysporium* and *Verticillium* sp.	Extracellular	20-50	(Bharde *et al.*, 2006)
Ag	*Fusarium semitectum*	Extracellular	10-60	(Husseiny *et al.*, 2015)
Ag	*Penicillium brevicompactum*	Intracellular	23-105	(Majeed *et al.*, 2016)
Ag	*Penicillium fellutanum*	Extracellular	1-100	(Kathiresan *et al.*, 2009)
Ag	*Phaenerochaete chrysosporium*	Extracellular	-	(Vigneshwaran *et al.*, 2006)
PbS	*Agpergillus sp.*	Extracellular	10-15	(Pavani *et al.*, 2012)
Ag	*Aspergillus niger*	Extracellular	40-45	(Prakash and Soni, 2012)

Recently, an advanced method for biosynthesis of small-size monodispersed AgNPs ranging from 1-7 nm reported in which electrochemically active biofilm (EAB) is used along with sodium acetate as an electron donor (Khan *et al.*, 2012). Similarly, gold nanoparticles biosynthesis is reported by ecologically important bacterial strains *Rhodopseudomonas capsulata* (Singh *et al.*, 2018), *Escherichia coli* (Mishra *et al.*, 2017), *Arthrobacter nitroguajacolicus* (Dehnad *et al.*, 2015), *Klebsiella pneumoniae* (Eren and Baran, 2019) and *Brevibacillus formosus* (Srinath *et al.*, 2018). The assumed mechanism for the reduction of metal during the biosynthesis of nanoparticles was found that an enzyme named nitrate reductase is responsible (Mewada *et al.*, 2013). The assumed hypothesis of silver nanoparticles (AgNPs) formation described that enzyme nitrate reductase followed by coenzyme nicotinamide adenine dinucleotide phosphate (NADPH), act as a reducing agent of silver nitrate salt (Ahmed *et al.*, 2020). Above mentioned biosynthesis of gold nanoparticles indicated that NADPH- and NADPH dependent enzymes did bio reduction for gold nanoparticles (Mewada et al., 2013). Bacterial synthesis of nanoparticles can be performed in two ways, i.e., intracellular and extracellular synthesis, as elaborated in Table 1. In extracellular synthesis, bacterial culture is centrifuged and precursor salt is added for reduction. Only bacterial metabolites in supernatant reduce salt for nanoparticle biosynthesis (Brown, 2002; Dimkpa *et al.*, 2018; Rani *et al.*, 2022). While in intracellular synthesis, precursor salt is directly added to bacterial culture for reduction mentioned in Table 3.

Fungi mediated nanoparticles

Nanoparticles fabrication using fungal strains is called myco-nanotechnology (Jabeen and Anum, 2020). The biosynthesis of nanoparticles by fungi has the following advantages compared to other microorganisms: it is easy to isolate, downstream processing is simple compared to bacteria, and fungi secrete a huge number of extracellular enzymes for nanoparticle reduction. Moreover, fungi have wider diversity range than other microbial reducers (Rao *et al*., 2017). Mycosynthesis of silver nanoparticles (AgNPs) has been reported by silver nitrate ($AgNO_3$) as precursor salt, which has been reduced by following fungal supernatants: *Aspergillus terreus* (Verma *et al*., 2010), *Fusarium acuminatum* (Premnath *et al*., 2021), *Fusarium pallidoroseum* (Shukla *et al*., 2022) were formed and studied by their applications mentioned in Table 2.

Table 3. Biosynthesis of nanoparticles by plants

Nano particles	Plant extract	Intra Extra cellular	Size (nm)	References
Au	*Acanthella elongate*	Extracellular	7-20	(Schabes-Retchkiman *et al*., 2006)
Ti/ Ni bimetallic	*Alfalfa*	Extracellular	1-4	(Schabes-Retchkiman *et al*., 2006)
Ag	*Aloe vera*	Extracellular	15.2 ± 4.2	(Tippayawat *et al*., 2016)
Au	*Avena sativa*	Extracellular	5-20	(Armendariz *et al*., 2004)
Ag, Au and Ag/ Au bimetallic	*Azadirachta indica*	Extracellular	50-100	(Shankar *et al*., 2004)
Ag/ Au	Black tea leaf	Extracellular	-	(Kathiresan *et al*., 2009)
Ag	*Capsicum annum*	Extracellular	10-40	(Li *et al*., 2007)
Ag	*Carica papaya*	Extracellular	60-80	(Shan and Tong, 2013)
Ag	*Cinnamomum camphora*	Extracellular	5-40	(Huang *et al*., 2007)
Ag	*Coriandrum sativum*	Extracellular	-	(Huang *et al*., 2007)
Ag	*Jatropha curcas*	Extracellular	10-20	(Chauhan *et al*., 2016)
Ag	*Sesuvium portulacastrum*	Extracellular	5-20	(Nabikhan *et al*., 2010)
Ag	Marigold flower extract	Extracellular	5	(Singh *et al*., 2018)
Ag	*Rosmarinus officinalis*	Extracellular	5-10	(Ghaedi *et al*., 2015)
NiO	*Aspalatus linearis*	Extracellular	100	(Mayedwa *et al*., 2018)
CeO NPs	*Hibiscus sabdariffa*	Extracellular	3.9	(Thovhogi *et al*., 2015)
Gold	*Garcinia mangostana*	Extracellular	32.96 ±5.25	(Lee *et al*., 2016)
ZnO NPs	*Moringa oleifera*	Extracellular	15-20	(Lee *et al*., 2016)
NiO	*Moringa oleifera*	Extracellular	305-410	(Elumalai *et al*., 2015)

Gold nanoparticles (AuNPs) have been reported as a comprehensive range of research tools in the biomedical, health and agriculture sector due to their biostability and compatibility. In fungus-mediated gold nanoparticles synthesis, two precursors are recommended: AuCl and $HAuCl_4$. They dissociate into Au^+ and Au^{3+} (Kitching *et al*., 2015). When the endophytic fungal strain *Aspergillus clavatus* is incubated with these ions they produce gold nanoparticles of size ranging from 20-35 nm (Verma *et al*., 2010). Extracellular synthesis of silver and gold nanoparticles (Ghosh *et al*., 2022), bimetal Au-Ag alloy nanoparticles and CdS nanoparticles were reported by the fungal strain *Fusarium oxysporum* (Tandon and Singh, 2014). Some other fungal strains were also reported for biosynthesis of other metallic nanoparticles like iron nanoparticles (Singh *et al*., 2018), PbS nanocrystals and bimetallic nanoparticles. Nanoparticles synthesized from fungus have high monodispersity and dimension(Abdel-Aziz *et al*., 2018). Proteins secreted from fungi reduced metals for nanoparticle synthesis efficiently and quickly by nonhazardous processes (Khan *et al*., 2017). Table (2) shows that most studies showed silver nanoparticle synthesis. Few other studies indicated other metal nanoparticles like magnetite, silica and titanium (Monrás *et al*., 2012).

Biosynthesis of nanoparticles by plants

Nanoparticle synthesis by plants is comparatively easier and more efficient than bacteria and fungi-mediated nanoparticles. One of the major problems of microbial culture is to keep contamination free, which is quite time-consuming and difficult to maintain cultures safe (Khan *et al*., 2022; Shafqat *et al*., 2023b). Moreover, plant mediated nanoparticles are used for the large scale production of nanoparticles without any contamination (Iravani, 2011). A wide range of plant species are reported for biosynthesis of nanoparticles (Makarov *et al*., 2014).

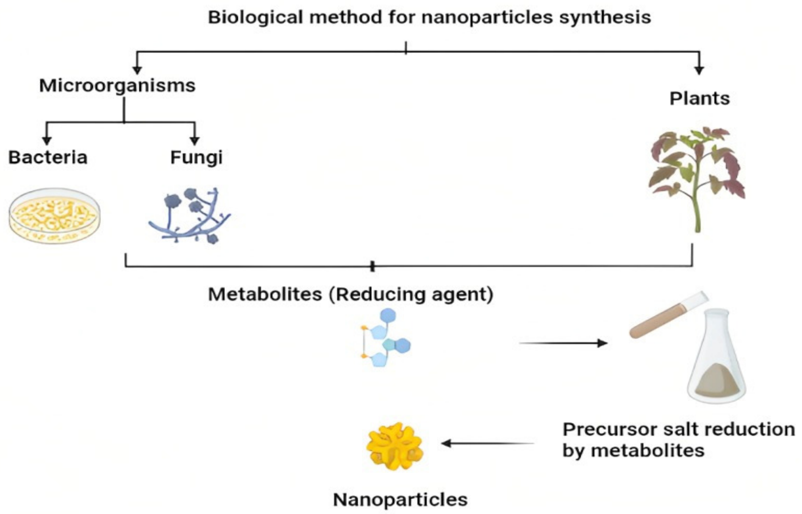

Figure 3. Elaboration of biological synthesis of nanoparticles

Silver nanoparticles photosynthesis reported by various plant extracts, i.e., *Zea mays* (Eren and Baran, 2019), *Azadirachta indica*, *Aloe vera* (Verma *et al*., 2011), *Oryza sativa*, *Saccharum officinarum Halianthus annus*(Velu et al., 2017) and *Sorghum bicolar*, (Frizzi and Huang, 2010). For zinc nanoparticles, members of the family Lamiaceae extensively used, like *Vitex negundo*, *Aniscohilus carnovus* (Anbuvannan *et al*., 2015). *Plectranthus amboinicus* (Zheng *et al*., 2019)and *Mentha piperita* (Babu Maddinedi *et al*., 2017)because as the concentration of plant extract increased, the size of nanoparticles reduced (Babu Maddinedi *et al*., 2017).

Table 4. Bacterial diseases of wheat

Disease	Causative agent (Bacteria)	Region/ Country	Losses	References
Bacterial leaf blight	*Pseudomonas syringae* subsp. *syringe*	Worldwide	13-14%	(Swings *et al*., 1990)
Bacterial mosaic	*Clavibacter michiganensis*	USA	18%	(Carlson, 1982)
Bacterial sheath rot	*Pesudomonas fuscovaginae*	Mexico	7%	(Zeigler, 1987)
Basal glume rot	*Pesudomonas syringae* pv. *atrofaciens*	Europe, New Zealand, Mexico, Syria	5-20%	(Wilkie, 1973)
Bacterial leaf streak	*Xanthomonas translucens* pv. *Undulosa*	Worldwide, Brazil, Mexico, Pakistan, USA, China	10-40%	(Zarinkoob *et al*., 2021)
Pink seed	*Erwinia rhapontici*	USA, Canada, UK, France	7-9%	(Forster, 1990)
Tundu or yellow ear rot	*Rathayibacter tritici* *Clavibacter tritici* *Corynebacterium michiganense* pv. *Tritici* Clavibacter ironic	India, China, Ethiopia, Egypt, Australia, New Zealand, Pakistan	8-20%	(Bhatti, 1989)

Zinc nanoparticles biosynthesized from *Vitex negundo* 38 nm size by XRD (Ambika and Sundrarajan, 2015). Zinc nanoparticles have wide range of threshold as compared to other nanoparticles they can be used up to 1000 ppm, and even at this concentration nanoparticles do not show toxic effects (Rana *et al*., 2019). Table 3 shows extracellular synthesis of nanoparticles. Mostly, micronutrient metals have been synthesized as nanoparticles like zinc, iron and copper, but some metal nanoparticles like gold and silver have also shown potential for various applications (Elumalai *et al*., 2015).

Table 5. Bacterial diseases of maize

Disease	Causative agent (Bacteria)	Region/ Country	Losses	References
Bacterial leaf blight and stalk rot	*Pseudomonas avenas* subsp. *avenae*	Worldwide	21-92%	(Goszczynska *et al*., 2007)
Bacterial leaf spot	*Pantoea ananatis*	South Africa, Argentina, Brazil, USA	50%	(Alippi and López, 2010)
Bacterial stalk rot	*Erwinia dissolves* *Erwinia chrysanthemi*	USA, India, Argentina, Brazil, China, India	2-25%	(Zhao *et al*., 2005)
Bacterial stalk and top rot	*Erwinia carotovora* subsp. *carotovora* *Erwinia chrysanthemi* pv. *zeae*	Worldwide	98.9%	(Sinha and Prasad, 1977)
Bacterial stripe	*Pseudomonas andropogonis*	Worldwide	10-35%	(Shen *et al*., 2009)
Bacterial wilt and blight	*Clavibacter michiganensis* subsp. *nebraskensis* = *Corynebacterium michiganense* pv. *Nebraskense*	USA	50.9%	(Langemeier *et al*., 2017)
Stewarts disease (Bacterial wilt)	*Erwinia stewartii*	South America, North America, Europe, Asia	15-40%	(Pataky, 2003)
Corn stunt	*Spiroplasma kunkelii*	American region	Upto 100%	(Premnath *et al*., 2021)

Role of nanoparticles in plant pathology

Nanotechnology in agriculture as agrochemicals has become more common as technological revolution occurs because of their economic production. The main requirement for nano-sized particles usage in agriculture is information about the antimicrobial activity of phyto pathogens and the development of better strategies for the suppression of diseases (Elmer and White, 2018). Plant extract, which later reduce or oxidize precursor salt extracted from plant organs like leaves, root and flower. Most of the time, leaf extract is is used for plant mediated nanoparticles (Vijayaraghavan and Ashokkumar, 2017). Silver nanoparticles proved very effective against two plant pathogenic fungi, *Magnaporthe grisea* (Elamawi and El-Shafey, 2013), *Bipolaris sorokiniana Alternaria solani*, *Erwinia carotovora* pv. *Carotovora* and Alternaria blight (Mishra *et al*., 2017) and *Phytophthora* blight (Zakharova *et al*., 2017). Meanwhile, *Aloe vera* and some other xerophytes are also used for the biosynthesis of silver nanoparticles. Specific phytochemicals of xerophytes are responsible for reduction of silver ions (Osagie *et al*., 2021). Cell death was recorded by the authors due to the entry into the bacterial cells of the nanoparticles due to the damaging of bacterial cell wall (Slavin *et al*., 2017). Mechanism of the bactericidal mechanism of nanoparticles is elaborated in Figure 4. Nanoparticles deregulate bacterial growth by retarding bacterial cells (Siddique *et al*., 2021).

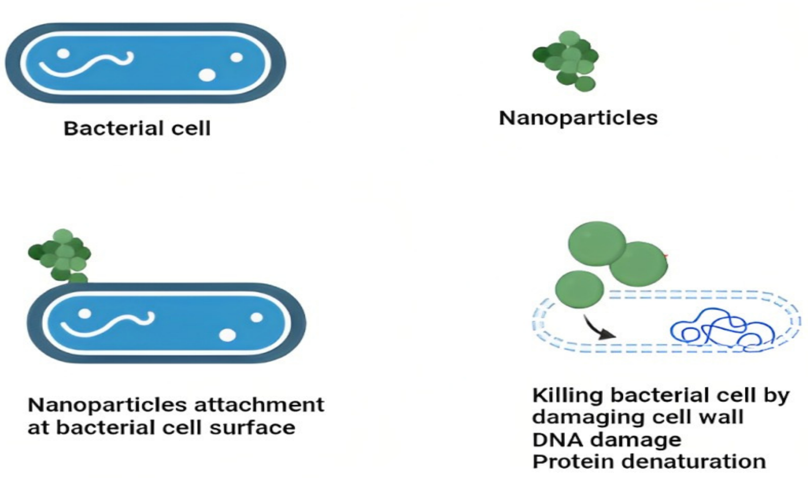

Figure 4. Mechanism of bacterial cell degradation through nanoparticles

Diligent investigative research is required because the effect of nanoparticles on the crop plant is an emerging area of the research. In recent times, engineered nanoparticles have become very important for improving the crop yield. Nanoparticles of micronutrients mitigate bacterial diseases by boosting the antioxidant defence of cereals (Rastogi *et al*., 2017). Nanoparticles were mainly used for the controlled release of the agro-chemicals and the delivery of the different macro-molecules which are necessary for improved resistance to plant disease, efficient use of nutrients & enhanced growth at the site Roopan (Rajakumar *et al*., 2012). It was recorded by the researchers that the comparative effects on plant growth with the use of nanoparticles. On treatment with the iron oxide nanoparticles, improvement in the pod weight, leaf & pod dry weight and soy bean yield was reported (Shen *et al*., 2009). No extraordinary growth difference of *Sesbania* seedlings in controlled or treated seedlings was observed when treated with gold nanoparticles, even when the concentration of gold nanoparticles in the solution was more than 200 ppm (Siddiqi and Husen, 2016). A decrease in *Cucurbita pepo* growth has been recorded due to the treatment with the nanoparticles of copper and silver (Tamez *et al*., 2019). According to the report the negative effects were recorded on phytoplankton growth due to the fact that silver nanoparticles were deployed. Due to their enhanced surface area to volume ratio, metal nanoparticles display more surface area besides bio-molecule valance electron exchange (Tsiola *et al.*, 2018). The metal nanoparticles induce antioxidant potential in stressed plants by increasing antioxidants and reducing ROS, H_2O_2 and oxidants. The lettuce seeds were determined by the root/shoot ratios of a germinated plant ($P < 0.05$) in all nanoparticles examined in the sample. The possible environmental implications of processing nano-materials are significant factors of phytotoxicity. The outcome for *Arabidopsis thaliana* (Mouse-ear cress) has been recorded of four metal oxides nanoparticles, aluminium oxide, silicones, magnetite and zinc oxide nanoparticles (Vankova *et al.*, 2017). Zinc nanoparticles raised the amount of IAA in *Cicer arietinum* seeds and the growth rate is increased because zinc is an essential nutrient of plants (Medda *et al.*, 2014).

Table 5. Bacterial diseases of rice

Disease	Causative agent (Bacteria)	Region/ Country	Yield loss	References
Bacterial blight	Xanthomonas oryzae *pv. oryzae = X. campestris pv. oryzae*	Worldwide	20-30%	(Zeigler, 1987)
Bacterial leaf streak	*Xanthomonas oryzae pv. oryzicola*	Tropical Asia, West Africa, China, India, Vietnam, Bangladesh, Indonesia, Malaysia	1.5-17%	(Swings *et al.*, 1990)
Foot rot	*Erwinia chrysanthemi*	Japan, India, Bangladesh, Korea, Philippines	20-70%	(Ruhl *et al.*, 2009)
Grain rot	*Burkholderia glumae* *Pseudomonas glumae*	Japan, Korea, Taiwan	34%	(Tsushim and Naito, 1991)
Sheath brown rot	*Pseudomonas fuscovaginae*	Asia, South America, Central Africa, Madagascar	58-70%	(Zeigler, 1987)

Table 6. Bacterial diseases in pearl millet

Diseases	Causative agent (Bacteria)	Region/Country	Yield loss	References
Bacterial leaf spot	*Xanthomonas eleusinae*	Worldwide	28%	(Shekhawat and Srivastava, 1972)
Bacterial leaf streak	*Pseudomonas eleusinae*	India	3-35%	(Kumar and Srivastava, 2020)
Bacterial blight	*Xanthomonas axonopodis* *Acidovorax avenae*	India, Africa	20%	(Mudingotto *et al.*, 2002)

Table 7. Bacterial diseases in oats

Disease	Causative agent	Region/ Country	Losses	References
Bacterial blight (halo blight)	*Pseudomonas syringae* pv. *coronafaciens*	Australia, Europe, North America, South America	-	(Harder and Harris, 1973)
Bacterial stripe blight	*Pseudomonas syringae* pv. *striafaciens*	Australia, Europe, North America, South America	-	(Elliott, 1920)
Black chaff and bacterial streak (stripe)	*Xanthomonas campestris* pv. *translucent*	Worldwide	-	(Duveiller, 1994)

The assessment was carried out, and good effects of Zinc oxide nanoparticles on the roots of *O. sativa* L. were recorded (Sahoo *et al.*, 2007). The associations of Zinc oxide (nano-ZnO), iron oxide (nano-FeO), and the combination of these oxides with Cu (nano - ZnCuFe – oxide) and *Vigna* radiate & their function as micronutrients have been documented. Molecular methods and enzyme studies have examined the impact of IOMNPs (Fe_3O_4) on the soil bacterial culture. The effects of silver nano-particles on the crops such as barley, wheat, brassica and radish have been recorded, and no major harmful effects of nanoparticles on any plant species have been recorded(Jyothi and Hebsur, 2017). The direct influence of gold nanoparticles on different growth and production parameters, including plant height, stem diameter, number of branches, number of pods and seed yield, is positive. Through use of nanoparticles in the agricultural sector may also help grow crop production and growth, accompanied by the containment of phytopathogen (Mishra *et al.*, 2020). The above-mentioned nanoparticles can be used against bacterial diseases of rice mentioned in Table 5 pearl millet mentioned in Table 6 and oats in Table 7.

Conclusions

Rather than using commercially accessible synthetic pesticides exhibiting higher toxicity to humans, biosynthesised nanoparticles may be used successfully against plant phytopathogens to protect different cereal crops and product lines. It can therefore be said that certain nanoparticles have no significant adverse effect on the germination of seeds, the root-shoot ratio and the microflora of the root zone, though some are advantageous to the plant species and in favour of farmers. Numerous nanomaterials, engineered nanoparticles, NPs of iron oxide, NPs of gold, and even a silver ion can quickly be synthesized and used as a pesticide. Finally, we can conclude whether nanobiotechnology is a significant line of study considering the potential applications to agriculture that, deserves all our focus.

Prospect in order to encourage cultivation there has been considerable interest in using nanoparticles against phytopathogens. In the near future the use of NPs for both the transmission of antimicrobials or drug molecules for the treatment of all the pathological diseases of plants would be at front position. It seems highly exciting to use nanoparticles as a fungicide for other crops. To discover the phytotoxic response of nanoparticles and their absorption by plants as micronutrients and the long-term effects of nanoparticles also at the microscopic level in crops, even more research should be done. Although these concerns appear to be discussed in additional research, attempts should be made to understand the better relationship between the various types of nanoparticle micronutrients, the plant, and the large assortment of pathogens of plants that mostly attack them.

Authors' Contributions

Conceptualization, FM and MS.; writing—original draft preparation, F.M.; U.S.; A.M.; A.I.; S.M.; Y.R.; and M.U.H. Writing—review and editing, J.M.A.; M.I.A.; M.N.S.; A.A.R.; M.I.A.; W.A.S.; and R.A.S.

All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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