15 Nanomaterials for Integrated Crop Disease Management

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Abstract

Because of the rising food demand, climate change, and environmental pollution, the global agricultural system is under increasing stress. In the current era, nanotechnology has demonstrated several applications in a variety of areas, including agriculture, medicine, and drugs. Due to their nano size, the increased surface to volume ratio, and unique morphology, nanoparticles have different characteristics than bulk materials. Nanoparticulated systems are being developed for use as fertilizers, insecticides, herbicides, sensors, and quality enhancers in agriculture. The present chapter discusses the use of nanoparticles (NPs) to improve sustainable agriculture and the environment by managing plant diseases directly as well as indirectly. The use of nanoparticles in plant disease control is a potential method for dealing with global concerns and ensuring sustainable crop production. This chapter will cover the basics of nanoparticles (NPs) and their uses in plant disease control. Plant disease management via the use of non-conventional nano-pesticides and fertilizer can play a pivotal role in mitigating the global food challenges and agricultural pollution concerns.

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15.1 Introduction

Agricultural pests and pathogens are responsible for 20–40% of crop losses each year globally (Worrall et al. 2018; Mesterházy et al. 2020). Despite many advantages, such as high availability, quick action, and effectiveness, pesticides exert negative impacts on non-target species, resulting in insecticide resistance. Furthermore, during or after the application, about 90% of applied pesticides are lost (Ghormade et al. 2011; Willkommen et al. 2021; Spinozzi et al. 2021). So, there is a greater need to produce efficient, high-performance, and low-persisting pesticides that are also environmentally friendly (Hatami et al. 2021). Nanotechnology has helped to make new agricultural ideas and products that have a lot of potential to help solve the problems (Worrall et al. 2018).

Nanoparticles (NPs) possess characteristics that differ from bulk and macroscopic materials, and these differences influence their destiny and impact on the biotic and abiotic components (Klaine et al. 2008; Gonçalves et al. 2021). The nanoparticles (NPs) are nanometer-sized particles that have shown some beneficial properties for sensing and detecting biological activities and structures in living bodies (Singh et al. 2008; Nie et al. 2021). Their size, large surface area, reactivity, absorbance, and aggregation govern their adherence to the soil as well as their subsequent mobility and movement (Borm et al. 2006; Xu et al. 2022). Although the NPs are used as antimicrobial agents against disease-causing bacteria, their overuse is hampering soil biodiversity, which executes important natural functions such as plant development, element cycling, and pollutant breakdown (Molina et al. 2006). As such, nanomaterials (NMs) are an important component of both biotic and abiotic remediation efforts because they interact with soil contaminants, affecting their toxicity, fate, and mobility (Usman et al. 2020). Rapid advances in nanotechnology have prompted concerns about the incidence, distribution, destiny, and mobility of NPs in the environment (Kurwadkar et al. 2015). Nanotechnology can help to ensure food security by improving crop productivity because NPs have the potential to improve plant development and production (Sadak 2019). They act as "magic bullets," holding fertilizers, genes, herbicides, or nano-pesticides, and concentrating their contents on certain cellular organelles in the plant (Siddiqui et al. 2015). NPs may be naturally or synthetically originated (Khan 2020). They can serve as a source of nutrients by ensuring their slow and controlled release, particularly micronutrients, and thus, limiting their access to the surrounding environmental barriers, as plants only require a small amount of these minerals (Tripathi et al. 2015; Dimkpa and Bindraban 2017). The NPs synthesis plays an important role in their properties. That's why several synthesis techniques are being researched to improve their qualities while decreasing the manufacturing costs (Kim et al. 2013; Jamkhande et al. 2019). Some techniques are modified to improve the mechanical, optical, chemical, and physical characteristics of individual nanoparticles (Cho et al. 2013). A significant advancement in instrumentation has resulted in the enhancement of their characterization as well as their application.

Plants, the most significant part of the terrestrial ecosystem, play an important role in nanoparticle uptake and transport through absorption and bioaccumulation (Monica and Cremonini 2009). The response of plants to nanoparticles is of great interest (Dimkpa et al. 2013; Hernandez-Viezcas et al. 2013), as the use of NPs as nano-pesticides has the ability to revolutionize agriculture (Adisa et al. 2019). Due to their physicochemical properties, NPs have a lot of potential in agriculture. The NPs–plant interactions cause a range of genotoxic, physiological, and morphological changes that must be understood for nanotechnology to be employed effectively in agriculture, especially in integrated disease management (Nair 2016; Elmer et al. 2018). The size of plant tissues and cells is the first requirement for NP penetration. Plants allow NPs with a diameter of 40–50 nm to easily enter and translocate into their bodies (Sabo-Attwood et al. 2011). For penetration, NPs adopt either apoplast or symplast transportation to travel through tissues. Plant cell NPs travel across the extracellular space of the plasma membrane to reach plant cell vessels in apoplast transportation (Sattelmacher 2001). Apoplast transportation enables NPs to travel radially across the plant's vascular system and into the central cylinder of the roots. NPs are transported by cell sieves and plasmodesmata during symplast movements (Roberts and Oparka 2003). This chapter is a brief review of the potential role of nanoparticles in plant disease management.

Owing to the immense potential use of nanotechnology and nanoparticles, their potential in pest and disease management of plants is also being explored, in which metal-based nanoparticles are very important. This chapter is a review of all the potential applications of nanoparticles in plant disease management.

15.2 Nanoparticles: Types, Synthesis, and Classification

The nanoparticles are a diverse class of chemical compounds made in a special way to get particle size on the nm scale. The nanoparticles can be organic (including dendrimers, micelles, liposomes, and ferritin) or inorganic (metal, metal oxide, mixed, metalloid, or beneficial nutrient NPs) in nature. The most widely employed metals for nanoparticle synthesis are aluminum (Al), zinc (Zn), cobalt (Co), silver (Ag), copper (Cu), gold (Au), and iron (Fe). Metal oxide nanoparticles are produced largely for their improved efficiency and reactivity. Magnetite (Fe_3O_4), cerium oxide (CeO_2), iron oxide (Fe_2O_3), zinc oxide (ZnO), silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and titanium oxide are some of the most frequent metal/metalloid oxide NPs (Tiwari et al. 2008; Salavati-Niasari et al. 2008).

Nanoparticles can be manufactured in several ways, including bottom-up or top-down methods. Bottom-up or constructive material accumulation refers to the accumulation of material from a single atom to clusters, which are subsequently turned into nanoparticles. Sol-gel, biosynthesis, pyrolysis, chemical vapor

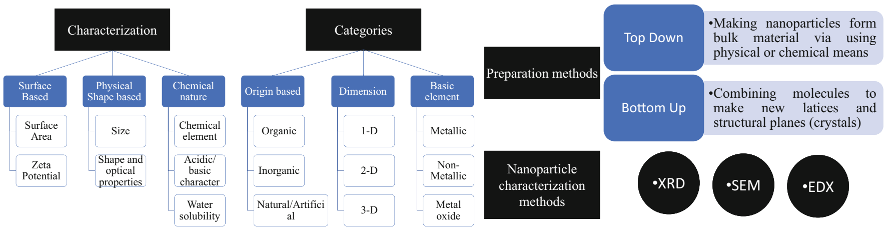

Fig. 15.1 Synthesis, types, and classification of nanoparticles (NPs)

deposition, and spinning are the most frequently utilized bottom-up procedures for nanoparticle production. A top-down or destructive technique is used to reduce a bulk material to nanometric-sized particles. Top-down nanoparticle production methods include mechanical milling, nanolithography, laser ablation, sputtering, and thermal breakdown. In the classification of nanoparticles, shape (2D-3D) and particle size (spherical, rods, crystals, etc.) are important, while the chemical nature of nanoparticles is also used to classify them (organic, inorganic, metal/metalloid/ metal oxide-based, etc), as explained in the literature reviews (Sohail et al. 2019, 2021). Figure 15.1 is a pictorial summary of the NPs' preparation methods and classifications.

15.3 Cereal Disease and NPs Interaction

The NPs can be utilized to fight arthropod pests, as well as to develop new insect repellants, insecticides, and insecticide formulas (Barik et al. 2008). The nanoencapsulation technology is used to deliver chemicals such as pesticides to a specific plant as a host, with the goal of controlling insect pests. The nanoencapsulated insecticides benefit plants by absorbing poisons (Scrinis and Lyons 2012). Nanoencapsulation is now seen as the most promising method of shielding host plants against insects and pests. Plants have been observed to absorb a nano-silica-silver silicon composite that helps them cope with stress and sickness (Brecht et al. 2003). Pathogenic bacteria that cause powdery mildew or downy mildew in plants are believed to be effectively suppressed by an aqueous silicate solution. It also increases plant growth and physiological development, as well as stress and disease tolerance (Kanto et al. 2004). Plant nanotechnology also has an important application in gene transfer technology, assisting in the provision of plant protection via chemicals as well as DNA delivery to receptor cells of plants (Wang et al. 2016). In this regard, nanoencapsulation is an important tool for the potentially slow and timely release of encapsulated chemicals for a prolonged time period. This can have a higher efficiency compared to traditional pesticides prone to runoff and leading to the human food chain (Agrawal and Rathore 2014; Khot et al. 2012).

15.3.1 Nano-pesticide

A nano-pesticide is a pesticide formulation or product that contains engineered nanoparticles with biocidal properties as active ingredients (A.I), either as a whole or as part of the designed structure (Kah and Hofmann 2014). In the presence of specific NMs, slow degradation and regulated release of active components may provide long-term pest control (Chhipa 2016). Nano-pesticides are required for the effective and long-term control of a wide range of pests, and they can assist in minimizing the use of synthetic chemicals and the environmental dangers that come with them. Due to their tiny size, nano-pesticides function differently than regular pesticides, and plants may absorb them more quickly (Kah et al. 2019). Kumpiene et al. (2008) suggest that nanoparticles may be transported in two ways: dissolved and colloidal. This explains why they act differently from other forms of solutes.

Rice (*Oryza sativa* L.) is a widespread staple food that is grown on vast swaths of fertile land all over the world (Zhu et al. 2017). Approximately 90% of the world's rice is grown in Asia, while China is one of the world's largest rice producers (Zahra et al. 2018; Li et al. 2015a, b). Plant diseases are the most important biotic restrictions on crop output in agriculture, and they have the potential to cause worldwide food devastation (Khoa et al. 2017). The most frequent bacterial pathogen in rice is Xanthomonas *oryzae pv. oryzae*, which causes bacterial leaf blight (Ryan et al. 2011; Udayashankar et al. 2011). Biogenic silver nanoparticles (AgNPs) have received a great deal of interest due to their exceptional biological, physicochemical, and antibacterial properties in decreasing plant illness (Adil et al. 2015). Wheat, after rice, is regarded as a basic grain due to its great nutritional content and numerous applications (Peng et al. 2011). In spite of other biotic stress-causing agents, various fungi have severely damaged the wheat crop, resulting in a 12.4% yearly yield loss worldwide (Galvano et al. 2001). A nano-pesticide is a pesticide formulation or product that contains engineered nanoparticles with biocidal properties as active ingredients, either as a whole or as part of the designed structure (Kah and Hofmann 2014). In the presence of specific NMs, slow degradation and regulated release of active components may provide long-term insect control (Chhipa 2016). Nano-pesticides are needed for the effective and long-term control of a wide range of pests, and they can assist in reducing the use of synthetic chemicals and the environmental dangers that come with them. Due to their tiny size, nano-pesticides function differently than regular pesticides, and plants may absorb them more quickly (Kah et al. 2019). Because nanoparticles (NPs) may be delivered in two states: dissolved and colloidal, they act differently than conventional solutes (Kumpiene et al. 2008).

Planthoppers are a major threat to world rice production. In China alone, they damage over 20 million hectares of rice-growing land each year (Hu et al. 2019). Engineered nanomaterials (ENM) have the potential to be employed as nano-insecticides in agriculture (Adisa et al. 2019; Sun et al. 2019). The ENMs have also been demonstrated to penetrate rice cells, interact with DNA, and boost relative Os06g32600 expression, resulting in enhanced disease tolerance (Li et al. 2018). Insects have developed resistance to pesticides because of their widespread usage, raising concerns about the environment (Zhang et al. 2017a, b; Wang et al. 2018). While omethoate, imidacloprid, and acetamiprid have shown to be effective against wheat aphids, their poor persistence makes them unsuitable for use during epidemics. A 40% dilution of Omethoate EC demonstrated that it had no effect on the wheat aphids in a field experiment (Yu et al. 2019). Incorporating nanotechnology into pesticide formulations is a new strategy for prospective organic crop growth that reduces the indiscriminate use of synthetic pesticides, while also offering environmentally friendly applications (Kumar et al. 2019). The United States Food and Drug Administration has given chitin and its derivatives a safe (GRAS) designation as a food additive since they are non-toxic and have been reported to be safe for humans, cattle, and animals. Because of their biocompatibility, biodegradability, and lack of cytotoxicity, nano-chitin components have been widely employed in biomedical manufacturing (Yang et al. 2020). Nano-chitin whiskers are non-toxic at quantities less than 50 g mL^{-1} and exhibit a greater cytocompatibility at 200 g mL^{-1} (Zhao et al. 2019). Chitosan was shown to be the most efficient in pest management, with molecular weights ranging from 2.27105 to 5.97105 g mol^{-1} (Badawy and El-Aswad 2012). As a result, nano-chitin has a demonstrated pro-insecticidal effect on chemical pesticides while causing no harm to non-target populations.

In an investigation by Choudhary et al. (2019), the Zn-encapsulated chitosan nanoparticles were reported to have antifungal activity on maize crops. The potential foliar as well as seed treatment of Zn nanoparticles was also proved to be linked with the control of Curvularia Leaf Spot (CLS) disease in maize. The findings of Wagner et al. (2016) conclude that Zn nanoparticles can act as a non-persistent and economical antimicrobial agent against oomycete *P. tabacina*. Similarly, their toxicity against *Xanthomonas oryzae pv. Oryzae* is also reported by Ogunyemi et al. (2019) in addition to their well-established antifungal properties (Navale et al. 2015; Savi et al. 2015; Wagner et al. 2016). Another important element, silver (Ag) nanoparticles, also has been tested and their antimicrobial activity has been reported as they can interfere with the microbial enzymatic system (Kim et al. 2017).

It is reported that nanoparticles are helpful in controlling pathogens causing diseases like belly rot (*Rhizoctonia solani*), Common Root Rot (*Bipolaris sorokiniana*), rice blast fungus (*Magnaporthe grisea*), grey mould (*Botrytis cinerea*), seedling blight, foot rot, ear blight (*Fusarium culmorum*), cottony soft rot (*Scalrotinia sclerotiorum*), colletotrichum fungal plant pathogens (*Colletotrichum gloeosporioides*), and black-leg of seedlings (*Pythium ultimum*) (Park et al. 2006; Gopal et al. 2011; Rai et al. 2014; Yah and Simate 2015). The Ag nanoparticles have been reported to eliminate the effects of the sun-hemp rosette virus (Jain and Kothari 2014). That is the reason Ag NPs are being used in some commercial fungicides like Kocide® to control *Alternaria solani* (causative agent of early blight disease), as reported by studies (Nejad et al. 2016). The use of Ag NPs against insects is also reported as Ag NPs prepared from green methods exhibited larvicidal and toxicity against the house fly (Abdel-Gawad 2018) and the mosquito (C*ulex pipiens pallens*), respectively (Fouad et al. 2016). The study conducted by Ismail et al. (2016) reported that Se and Cu NPs can be an effective way of controlling the attack of Alternaria solani on tomato plants. The third important nanoparticle involved in the management of pests in plants is Cu, with its extraordinary antimicrobial properties reported for the control of disease spread by Xanthomonas sp. (Chhipa and Joshi 2016) and are widely being used because of their broad-spectrum antimicrobial properties (Esteban-Tejeda et al. 2009). The Cu nanoparticles have been reported to be effective against diseases like fusarium wilt and early blight, which cause diseases in tomatoes (Saharan et al. 2015). Furthermore, the insecticidal aspects of Cu nanoparticles are also present, as reported by Le Van et al. (2016), with Cu NPs in low concentration increasing the expression of Bt toxin protein, thus improving the pest resistance of transgenic cotton. The fourth important nanoparticle being used as nano-pesticide is silica (Si-NPs) and has been reported by various studies as presented in Table 15.1. The Si-NPs are reported to have lethal properties against *Callosobruchus maculatus* (Rouhani et al. 2012) and are being used in commercial pesticides to control the early blight of tomatoes (Derbalah et al. 2018) and spot diseases in dragon fruit (Tuan et al. 2018; Verma 2018). The role of Si-NPs in the control of various pests is also well reported for the control of lesser grain borer (*R. dominica*), confused flour beetle (*T. confusum*) (Ziaee and Ganji 2016), African cotton leafworm (*Spodoptera littoralis*) larvae (El-Helaly et al. 2016), and cowpea weevil (*Callosobruchus maculatus*) (Rouhani et al. 2012). Moreover, the application of Si-NPs has also been reported to control pests strains and diseases like *P. fluorescens* causing pink eye potato, the bacterial blast caused by *P. syringae* and *P. carotovorum* (Cadena et al. 2018), *Staphylococcus aureus, Proteus mirabilis, Pseudomonas aeruginosa* (Mohammadi et al. 2016), *Listeria innocua* (Ruiz-Rico et al. 2017), *Escherichia coli* (Mohammadi et al. 2016; Shevchenko et al. 2017), *Staphylococcus aureus, Aspergillus fumigatus* (Song et al. 2018), *B. subtilis, S aureus*, and *P. aeruginosa* (Tahmasbi et al. 2018) is also well known.

15.3.2 Nano-fertilizers

Fortifying wheat with essential micronutrients like zinc and iron is one approach for combating “secret hunger” in a major section of the world’s population and is also an integral part of integrated pest management, as a healthy plant can fight diseases very well. The availability of essential nutrients has imparted significant impacts on crop nutrition, health, and output (Chhipa 2016). Nanoparticles improve crop yield and ensure food safety either upon direct application to the soil or as foliar sprays to the plants (Dimkpa and Bindraban 2017). Large amounts of micronutrients used during fertilization can result in nutrient waste and environmental contamination. Therefore, the application of nano-fertilizers to the crops is considered a more efficient method due to the high penetration in the plant. “Nano fertilizers are synthesized or modified forms of conventional fertilizers, which can enhance nutrient use efficiency (NUE) via various mechanisms such as controlled release and target delivery. Moreover, they can release their active ingredients in response to environmental triggers as well as biological demands” (Solanki et al. 2015). The physical and chemical properties of nanoscale materials vary from those of bulk materials (Nel

Table 15.1 Effects of various nanoparticles in plants

Type	Source	Dose	Organism of action	Effect	References
ZnNPs	ZnNPs formed via green synthesis using **Sargassum vulgare**	Variable dose	Aspergillus, Candida *and* Saccharomyces cerevisiae	Potential antifungal activity was observed in the prepared NPs	Karkhane et al. (2020)
ZnNPs	Zn and ZnO	8 and 10 mg L^{-1}	*Peronospora tabacina* (Tabaco infecting pathogen)	Both doses as well as sources were found to be toxic for pathogen germination and growth, suggesting its potential role as nano-pesticide	Wagner et al. (2016)
ZnNPs	ZnO	0–100 mgL^{-1}	*Pathogenic bacteria and fungi*	Strong antimicrobial activity of NPs was observed owing to their capability in ROS production	Navale et al. (2015)
Zn compounds	Zn, ZnO, ZnSO4 and nano ZnO	Various doses	Fusarium head blight on wheat (*Triticum aestivum* L.)	Zn compounds in addition to existing formulations, can help in overcoming the deoxynivalenol formation in wheat plant	Savi et al. (2015)
Chitosan NPs coated with Zn	Zn-chitosan NPs	0.01–0.16%	Maize (*Zea mays*)	Zn-chitosan NPs proved to be helpful in promoting maize growth, disease control and help in nutrient fortification	Choudhary et al. (2019)
Se and Cu NPs	Se and Cu NPs	Foliar application of various doses	Tomato (*Solanum lycopersicum*) under fungal pathogen Alternaria solani attack	The exogenous application of Se and Cu-NPs helped enhance plant growth and control pathogen effect on the plant by improving contents of various inorganic and organic compounds	Ismail et al. (2016)
Carbon	Carbon nanoparticles	Variable doses	*Rice* (*Oryza sativa*)	The carbon nanoparticles helped rice plant in increasing plant growth as well as disease resistance	Li et al. (2018)
Silica and silver	SiO and Ag NPs	1–2.5 g kg^{-1}	Cowpea seed beetle *Callosobruchus maculatus F*	Both NPs have shown a potential effect on larvae mortality, suggesting their pesticide potential	Rouhani et al. (2012)

Silica NPs	Silica gel and silica gel NPs	Variable doses	Moth (*Tuta absoluta*)	Potential toxicity of NPs was observed for tested insects, larvae, and adults	Magda and Hussein (2016)
Silica NPs	Silica	–	Early blight of tomato (Alternaria solani)	The NPs have proven to be better antifungal agents compared to metalaxyl (commercially available fungicide)	Derbalah et al. (2018)
Silica NPs	Silica NPs	1% by wt in PDA media	*Trichoderma harzianum* and *rhizoctonia solani*	Antifungal properties were observed	Verma (2018)
nSiO_2–OC	Oligochitosan (OC) and nanosilica	–	Dragon fruit Brown spot disease caused by *Neoscytalidium dimidiatum* fungus	The NPs treatment enhanced chitinase production and helped in the reduction of disease severity	Tuan et al. (2018)
AgNPs	$AgNO_3$	500, 1000, 2000 & 4000 mg/L	*Spodoptera litura*	The growth index of lepidopteran species were decreased, damage to the nucleolus by the deposition of AgNPs in midgut cells	Yasur and Rani (2015)
AgNPs	Green synthesized Ag NPs	Variable doses	Cluster bean leaves inoculated with sunhemp rosette virus	The green synthesized ag NPs have shown a successful suppression of viral disease onset showing potential antiviral properties	Jain and Kothari (2014)
AgNPs	$AgNO_3$	30, 60, 90, 120 & 150 ppm	*Spodoptera litura* & *Helicoverpa armigera*	Damage the epithelial tissues and goblet cells of larval midgut of Spodoptera litua & Helicoverpa armigera	Manimegalai et al. (2020)
Ag and Zn NPs	Ag and Zn NPs prepared	Various doses	House Fly (*Musca domestica*)	The applied doses of NPs have shown positive effects on controlling early staged individuals of houseflies suggesting strong possible use as an alternative pesticide	Abdel-Gawad (2018)

(continued)

Table 15.1 (continued)

Type	Source	Dose	Organism of action	Effect	References
AgNPs	$AgNO_3$	100, 500, 1000 & 1500 mg/L	*Spodoptera litura*	Acute toxic effect on Spodoptera litura larvae, non-significant effect on the activity of detoxification enzymes (glutathione-s-transferase & carboxyl esterases enzymes)	Jafir et al. (2021)
Glass containing Cu NPs	Sepiolite fibres containing monodispersed Cu NPs	Variable doses	*Fungal species*	Ca(2+) lixiviated mediated toxicity to fungal species, suggesting the strong antifungal potential of hybrid nanoparticles	Esteban-Tejeda et al. (2009)
Carbon and Cu NPs	Chitosan, chitosan-saponin and Cu-chitosan nanoparticles	0.001–0.1% doses in invitro study	Phytopathogenic fungi (*Alternaria alternata*, *Macrophomina phaseolina* and *Rhizoctonia solani*)	Model has shown NPs capability in controlling fungal sprawl suggesting its long term and field application as a possible option	Saharan et al. (2013)
Cu-carbon	Cu-chitosan based NPs	Variable doses	*Alternaria solani* and *Fusarium oxysporum* affecting tomato plant	The model demonstrated a potential antifungal effect on both species suggesting the potential applicability of NPs in field conditions	Saharan et al. (2015)
ZnO, Cu, and Cu_2O/Cu	Zn and Cu nanoparticles	Variable doses	*F. oxysporum, F. solani, C. gloeosporioides*	A net inhibition of growth of all fungal species was observed	Pariona et al. (2021)
CuO-NPs	CuO	Variable dose	*Bt Cotton*	The exogenous application of CuO-NPs helped in gene triggering of crops involved in better disease prevention	Le Van et al. (2016)
CuO-NPs	$CuSO_4 \cdot 5H_2O$	100, 150, 200, 250 & 300 ppm	*Triticum aestivum*	Acute toxic effect against *Sitophilus granarius* and *Rhyzopertha dominic*, improves the plant physiology and yields related parameters	Rai et al. (2018)

CuO-NPs	Sigma–Aldrich	100 mg/L	*Galleria mellonella* L	Increases the activity of CAT & GST while decreasing the activity of SOD & AChE in the midgut of *Galleria mellonella* L	Tuncsoy et al. (2019)
CuNPs	NanoSany Corporation (Iran)	50, 100 & 200 ppm	Pepper	Transcriptionally down-regulates the MVK gene involved in the metabolism of terpenoids and upregulated the microR159 in pepper, increased concentration poses the oxidative stress, upregulates the activity of catalase, peroxidase, & polyphenol peroxidase	Tabatabaee et al. (2021)

et al. 2006). Nano-fertilizers penetrate the seeds and increase the nutritional status of seedlings, resulting in healthier and longer shoot and root lengths. Nano-fertilizers are classified as either micronutrient or macronutrient nano-fertilizers, depending on their nutritional status (Chhipa 2016). Plant metabolism is stimulated by nanoscale nutrient forms, which improve development, nutritional quality, and growth (Dimkpa and Bindraban 2017). Nano-fertilizers increase nutrient use efficiency, minimize important nutrient immobilization, and reduce nutrient leaching through agricultural run-off (Liu and Lal 2015). As compared to conventional fertilizers, nano-fertilizers enhance chlorophyll synthesis as well as the rate of photosynthesis, and thereby increase the transfer of the photosynthates to different plant parts and increase crop production (Ali and Al-Juthery 2017; Singh et al. 2017).

In waterlogged conditions, zinc (Zn) is an essential nutrient for rice growth and development (Naik and Das 2007). The foliar application of Zn to plants increases its concentration (Saha et al. 2017). The use of Zn nano-fertilizer benefits rice development by providing nutrients slowly during crucial periods (Yuva Raj and Subramanian 2021). The use of Si and Zn nano-fertilizers boosted the concentrations of essential plant nutrients silicon and zinc in rice plants by around 24% and 21%, respectively (Ghasemi et al. 2014). Nano-silicon fertilizers have high availability because of their small size and strong penetration power, whereas standard silicon fertilizers have low availability. Nano-silicon fertilizers, when compared to traditional Si fertilizers, can minimize silicon (Si) accumulation (Wang et al. 2016). It's a reported fact that micronutrients and beneficial nutrients can be very effective agents for plants to fight against diseases, and exogenous application of these nutrients can help plants in various diverse ways in coping biotic stress (Datnoff et al. 2007; Fones and Preston 2013).

15.4 Bioavailability, Concentration, and Toxicity of the Nanoparticles

Because many NPs contain biotic life, the incorporation of NPs into plant reproductive and eating tissues is of special importance (Rizwan et al. 2016). The absorption and transportation of the NPs depend upon the plant species, cultivars, and developmental stages (Anjum et al. 2015; Shi et al. 2014). Plant tissues' natural micro-meter or nanometer-scale pores allow NPs to attach to and pass through plant surfaces (Schwabe et al. 2015). The uptake of the NP is characterized as an "active-transport mechanism" because it involves a variety of cellular processes such as recycling, signaling, and plasma membrane regulation (Wang et al. 2012). Before adopting the apoplastic way to the epidermis and cortical cells, the NPs adhere to the root surface (Anjum et al. 2015, 2016). When NPs enter plants, they penetrate through the cell membrane and cell wall of root epidermal cells before being guided via the xylem (vascular bundle) by a series of complicated processes before being transported to the stele via the symplast route and are eventually translocated to the leaves. Cell membrane holes tailored to the size of the nanomaterial allow NPs to penetrate through the integral cell membrane (Tripathi et al. 2015). The NPs must be absorbed by a passive channel via the endodermal apoplast before they can get near to the stele (Judy et al. 2016). Xylem is a plant-based mechanism for allocating and transporting nanoparticles (Aslani et al. 2014).

15.5 Fate and Safety Aspects of Nanoparticles

The fast growth of nanotechnology has prompted concerns about the risks of a wide range of hazardous NPs, and their uncontrolled usage as nano-pesticide and nano-fungicide formulations should be monitored since they can contaminate the soil. In order to establish safe nanomaterial-based technology release mechanisms, the formation of these NPs in soil, and their absorption into the food chain, should be monitored. The NPs have been shown to exert dose-dependent toxicity in agricultural plants in several studies (Li et al. 2015a, b). Pure aluminum NPs, for example, inhibited root development in maize, tomato, cucumber, carrot, cabbage, and soybean plants (Hassan et al. 2013). Plant development is inhibited by alumina (Al_2O_3) NPs, which are contaminants in the environment. Tobacco seedlings demonstrated a continuous and significant reduction in average leaf count, biomass, and root length when exposed to high levels of Al_2O_3-NP (Burklew et al. 2012). Copper NPs were cytotoxic to mung beans, but Ag-NPs were cytotoxic to zucchini and onions. At higher concentrations, multi-walled carbon nanotubes (MWCNTs) have been proven to be cytotoxic in a variety of plants, including Arabidopsis and rice (Nair et al. 2010). These findings emphasize the need to understand the ecosystem's lowest safe NP threshold. Nano-ZnO, for example, is taken from the soil by the roots and accumulated in the edible parts of soybean plants, decreasing food quality. Similarly, nano-CeO_2 lowered soybean plants' capacity to fix nitrogen and hence reduced the yield.

15.6 Conclusion

Nanotechnology is a branch of science that has applications in a wide range of fields. Nanotechnology is undergoing intensive research in an attempt to commercialize it around the world. In agriculture, nanoparticles are used to reduce the use of plant protection chemicals, reduce nutrient losses, and boost yields. Because food demand is increasing every day and staple food crop yields are low, metal nanoparticles must be commercialized for sustainable agriculture. NPs promote plant metabolic activity and act as a plant nutritional fertilizer to boost crop yield. Every day, food demand rises while primary food crop yields diminish. Today, however, increasing the food supply is important in order to feed the world's growing population. Commercialization of metal nanoparticles for sustainable agriculture is consequently required.

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