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Review Article

Nanotechnology and Crop Protection: A Review of Principles and Prospects

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Abstract

Nanoparticles have numerous applications in agriculture, because of their great mobility in plant and animal cells and high penetrability. It has the ability to close the gap between farming that is sustainable and farming that is not. A significant issue in agricultural systems is post-harvest losses, which have been demonstrated to be decreased using nanomaterials. Ultra-small particles, known as nanoparticles, have distinct physical, chemical and biological characteristics. It has been discovered that nanopesticides and nanoinsecticides have improved pesticidal and insecticidal characteristics, can supplement traditional pesticides and are anticipated to completely transform pest management in the near future. Specific antibacterial potentials exist in nanoemulsions, nanoliposomes, edible coatings and other forms of nanoparticles like nanosensors that are used to facilitate the measurement and monitoring of crop production as well as the control of pests, diseases, insect attacks and environmental contaminants. The agricultural system makes extensive use of nanoparticles, particularly for plant infection prevention. Due to their small sizes, nanoparticles interact with plant pathogens more effectively and display their antibacterial properties when exposed to various bacteria that have developed resistance to antibiotics. Agricultural research using nanotechnology has recently focused on diagnosing plants, boosting output and developing new disease-resistant varieties. It has the potential to improve agricultural productivity, reduce disease tolerance, speed up the identification of plant illnesses and reduce input costs. In this review paper, the fundamentals, practices and future possibilities of nanotechnology in crop protection have been discussed.

Keywords: Crop pest; Crop protection; Nano insecticide; Nanoparticles; Nano pesticide; Post-harvest

Introduction

In order to avoid a decrease in food security as a result of agricultural produce loss and long-term damage to soil due to unsustainable agricultural practices, there is a need to explore new and promising methods that are sustainable and eco-friendly. Plants are usually faced with certain pest invasions either pre-harvest or post-harvest, which result in yield loss, the prolonged occurrence of pests in the soil and the development of resistant strains. The severity of the invasion can be reduced by the application of chemicals or by genetic engineering, which makes available the use of resistant cultivars. Both restorative methods are, however, expensive and sometimes not effective, especially against resistant strains of pests or pathogens. In recent studies, nanomaterials have been put into consideration as possible agents against pest and disease attacks on plants (Ghidan and Antary 2019; Um-e-Aiman *et al.* 2021). Nanoparticles have targeted characteristics as ideal commercial or domestic materials with functional applications in many fields such as disease diagnosis and curing, drug discovery and target delivery, antimicrobial application against

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multidrug resistant microorganism (Femi-Adepoju *et al.* 2019; Dada *et al*. 2018), environmental and energy-based research, catalysis and imaging, as well as in agriculture (Ibrahim *et al*. 2019).

There is an increase in the global population, which has placed pressure on the availability of food. The development of nanotechnological innovations in agriculture has therefore recently been able to bridge the gap that could be created by this mounting pressure. Farmers are integrating advanced agricultural techniques, such as the use of fertilizers, insecticides, *etc*. with nano-based materials to improve crop effectiveness (Gangwar *et al.* 2023). Aside from that, it has also encouraged the practice of sustainable farming in areas of crop protection, minimal agrochemical application for environmental biodiversity conservation, crop improvement to enhance adaptation and consequent survival, controlled pesticide or herbicide application delivery of balanced nutrition in crops, increased yield, crop sensitivity and perturbation measurement and monitoring. Therefore, nanomaterial technology supports many agricultural fields with a view to presenting a broader but crucial and specific technology to sustain precision agriculture. It will reduce unpredictability and control the strategies involved in the management of agricultural production (Shang *et al*. 2019; Guleria *et al*. 2023).

Nanotechnology is widely applicable in various fields, especially agriculture, because the technology involved has high penetrability and mobility in plant and animal cells. They are able to inhibit microbial growth by increasing the permeability of the membrane, preventing the biological synthesis of ethylene and increasing the activity of antioxidative enzymes (Ayesha *et al.* 2020). Also, nanotechnology has played significant roles in the improvement of plant growth, yield and development and in the formulation of fertilizers, insecticides, herbicides and pesticides. The nanomaterials used in the field of agriculture include but are not limited to nanoparticles as directly applicable substances to plants either to improve plant growth or enhance plant defense system mechanisms against infection, nanosensors for plant disease diagnosis and nanodevices used in genetic engineering and bioremediation processes (Ghidan and Antary 2019; Ayesha *et al.* 2020). Pests have been shown to be effectively controlled by the use of nanopesticides. A good deal of nanoparticles is put forward as pesticidal carriers and biological agents due to their inherent antimicrobial and pesticidal properties (Asif *et al.* 2022). Multifunctional N-doped nanomaterials such as ZnO and TiO_2 NPs have been tested for their pesticidal properties and found to be effective against plant insects, pathogenic bacteria and fungi (Quoc *et al.* 2020). The concept of nano-fortified pesticides is not a popularized concept yet and minimal information is available on large-scale field applications; therefore, much information is still lacking on their mode of action and consequential environmental effect (Kumar *et al.* 2018; Hamel *et al.* 2020; Singh *et al.* 2020). Biobased pesticides, including nanoebiotechnology, play a crucial role in managing insects and pests. These nontoxic, environmentally benign nanoepesticides contain MtNPs with superior antibacterial, antifungal and antipathogenic properties (Gupta *et al.* 2023). However, it is expected that potential nanopesticides should have a unique mechanism of action, be target-specific, inexpensive, stable and possess long-lasting activity even under different environmental applications (Singh *et al.* 2021).

Traditionally, quite a large number of conventional pesticides are needed to achieve the desired result, coupled with the problem of environmental toxicity, but nanomaterials can deliver at a higher efficiency level with reduced quantity (Huang *et al.* 2014, Singh *et al.* 2019). This makes nano-fortified pesticides better candidates for crop protection and preservation. Clay nanotubes, for example, have earlier been developed as nano-carriers of efficient pesticides with reduced environmental hazards (Singh *et al*. 2019). In this review, the role of nanotechnology in crop protection and especially in disease management to reduce the quality and quantity of crop loss is evaluated.

Nanotechnology and Synthesis

Nanoparticles are ultra-small particles with sizes ranging from 1 to 100 nanometers and have unique physical, chemical and biological properties that are different from their bulk counterparts (Gatea *et al.* 2022). The synthesis of nanoparticles is a complex, multi-step process that involves the creation of nanoparticles from precursor materials, followed by purification and functionalization (Wang and Chen 2018). There are several methods of synthesizing nanoparticles, including physical, chemical and biological methods.

The effectiveness and dependability of nanoparticles of different types depend on the mode of synthesis. With established facts. The chemical mode of synthesis is inferior to green synthesis. The well-known chemical method is expensive, complicated, time-consuming and environmentally toxic, while the green synthesis method is easy, cheap, saves time and is eco-friendly. Greenly synthesized nanoparticles are stabilized and usable by biological entities through the capping process, which makes them also be produced on a large scale (Maity *et al.* 2019; Ayesha *et al.* 2020). Especially plant-based nanoparticles have received more attention and more biological applications because of their environmental sustainability potential (Femi-Adepoju *et al.* 2018; Chen *et al.* 2019; Femi-Adepoju *et al.* 2019).

Physical methods of nanoparticle synthesis include physical vapor deposition, laser ablation and mechanical milling (Zhou and Wang 2015). Physical vapor deposition involves the condensation of vaporized materials onto a substrate, while laser ablation involves the rapid heating and cooling of the precursor material through laser irradiation

(Gatea *et al.* 2022). Mechanical milling involves the grinding and milling of the precursor material to produce nanoparticles (Wang and Chen 2018). Physical methods are widely used to produce nanoparticles because they are simple, cost-effective and can be scaled up for large-scale production. Physical methods are simple, cost-effective and can be scaled up for large-scale production.

Chemical methods of nanoparticle synthesis include solution-based methods such as co-precipitation, sol-gel and hydrothermal methods (Zhou and Wang 2015). Solution-based methods involve the formation of nanoparticles in a liquid solution, where the precursor materials are mixed and subjected to chemical reactions to produce nanoparticles (Gatea *et al.* 2022). Co-precipitation involves the formation of nanoparticles through the reaction of two or more precursor materials, while sol-gel involves the formation of nanoparticles through the hydrolysis and condensation of a precursor material (Wang and Chen 2018). Hydrothermal methods involve the synthesis of nanoparticles under high-pressure and high-temperature conditions (Zhou and Wang 2015). Chemical methods offer precise control over the size, shape and composition of the nanoparticles and are widely used for the synthesis of complex nanoparticles. Chemical methods offer precise control over the size, shape and composition of the nanoparticles.

Biological methods of nanoparticle synthesis involve the use of microorganisms, such as bacteria and fungi, to produce nanoparticles (Zhou and Wang 2015; Oluwasogo *et al.* 2023; Garg *et al.* 2024). These methods involve the biosynthesis of nanoparticles, where microorganisms and plant materials are used to convert the precursor materials into nanoparticles (Gatea *et al.* 2022). Biological methods are eco-friendly and offer the potential for large-scale production of nanoparticles (Wang and Chen 2018). Using plant extract to synthesize nanoparticles has gained attention because of characteristics like being reproducible, biodegradable and exhibiting efficacy against a wider range of pathogens (Banerjee *et al.* 2021). The choice of method depends on the specific requirements of the application and the desired properties of the nanoparticles. These methods are concisely presented in Fig. 1 and 2 below.

Nanomaterials for the protection of crops against pests and insects

Nano-formulations as bio-pesticides and bio-insecticides: As the world population increases, the demand for food, both in quality and quantity, increases. This high demand can only be met by increasing the technical skills required to improve agricultural production. It has been reported that annually, almost 25% of the world's crop is destroyed due to pests (Abu *et al.* 2022). Pests can pose a serious threat to the food supply as they are responsible for two major kinds of damage to growing crops. Direct injury to plants is caused by insects eating leaves and burrowing holes in stems, fruits and/or roots. Effective pest control for farms and agricultural premises is essential, hence the use of pesticides. Different pesticides, comprising chemical, synthetic, biological and botanical agents, have been adopted to achieve adequate results against pests for agricultural interests and plant safety. But due to direct chemical and synthetic pesticide poisoning, many people have been reported dead globally (Abu *et al.* 2022) due to their potential toxicity to humans and other species through the food chain (Lade *et al.* 2019). Due to the toxicity of pesticides, biopesticides as alternatives to manage pests on crop plants were one of the approaches that involved the use of biological sources to replace hazardous chemical pesticides.

Though there is still low awareness of the level of efficacy of nanopesticides and nanoinsecticides in contrast to traditional products, several reports have been documented about the enhanced pesticidal and insecticidal properties of nanoparticles. For instance, silver nanoparticles (AgNPs) synthesized using the extract of *Tinospora cordifolia* were subjected to insecticidal activity and found to inhibit the larvae of *Culex quinquefasciatus* and *Anopheles subpictus* (Kah *et al.* 2013). Some nanopesticides can also show augmentative effects on conventional pesticides by increasing their pesticidal activity, life span and stability (Banerjee *et al.* 2021). For example, pesticide avermectin has a short life span, which translates to short-term delivery and a quick end to the activity process. However, avermectin was combined with porous Si NPs and enhanced life span and stability were achieved (Ghormade *et al.* 2011). Cobalt-doped ferrihydrite ($5Fe_2O_3.9H_2O$) nanoparticles at 1.6 g L^{-1} in combination with a commercial fungicide that contains tebuconazole at 60 g L^{-1} and tiabendazole at 80 g L^{-1} have delivered enhanced pesticidal efficacy and also reduced their toxicity on the seeds of *Hordeum vulgar*. Aside from that, polyethylene glycol and isophthalic acid methyl ester fortified with pyrethroid cyfluthrin copolymer nanoparticles, when compared with commercial nanoformulations, have shown better effects against *Callosobruchus maculatus* for a period of 30 days (Pestovsky and Martnez-Antonio 2017). Nanopesticides are usually applied in small doses and provide more beneficial results. Green synthetic metal nanoparticles using various plant extracts as capping agents have shown varying degrees of pesticidal and insecticidal properties.

Biopesticides are substances or mixtures of biological substances used to prevent, destroy, kill, control, or mitigate pests. Pesticide plants, also known as botanical pesticides, are derived naturally from plants (Krishnamurthy *et al.* 2020). Biopesticides are also known as biological pesticides, insecticides derived from microorganisms or natural substances and can be categorized into three types: microbial biopesticides, botanical biopesticides and plant-incorporated biopesticide protectants (Mathew *et al.* 2014). Bioinsecticides are naturally occurring substances from different sources that control insect pests (Qu *et al.* 2022).

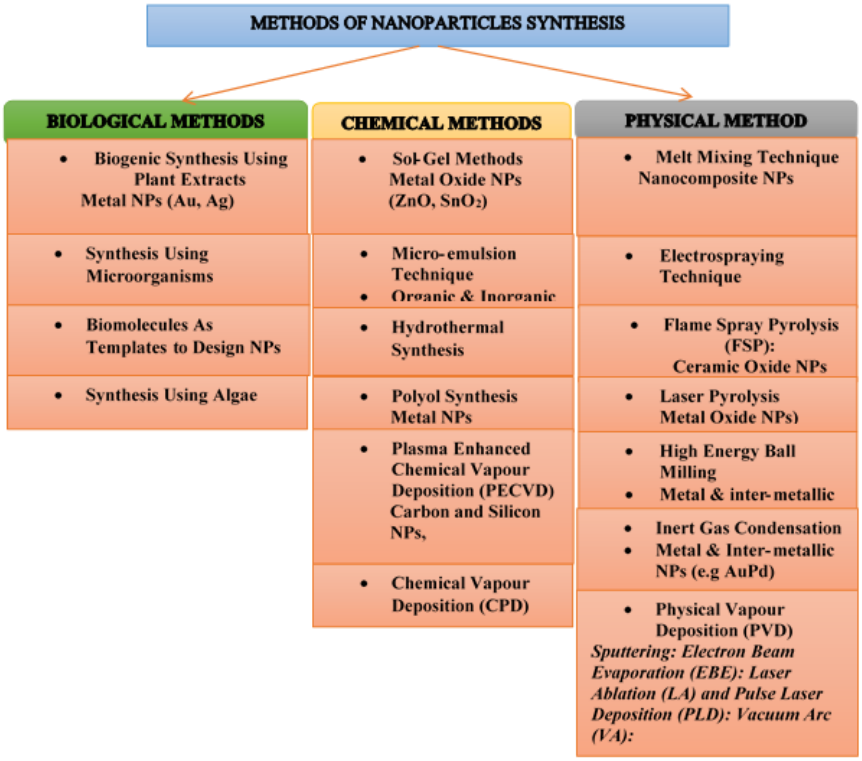


Fig. 1: The Different Methods of Nanomaterial Synthesis

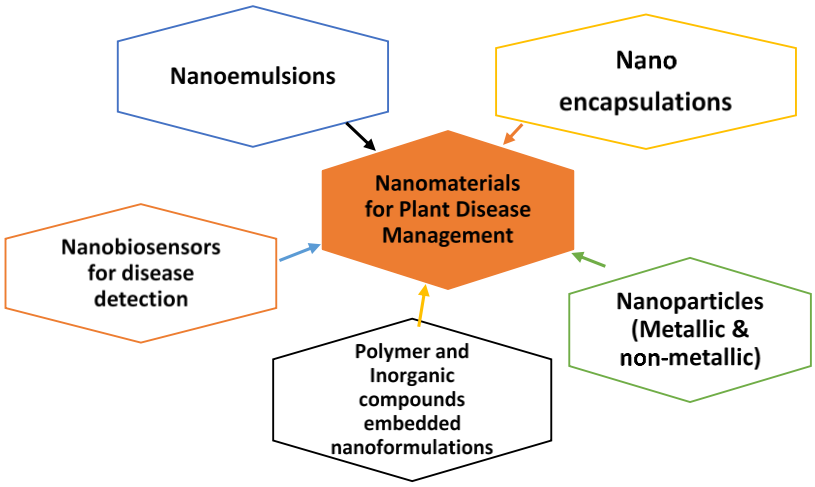


Fig. 2: Nanotechnological approaches for the management of plant diseases

Nanotechnology is one of the most important tools in modern agriculture and is expected to revolutionize the field of pest management in the near future (Bhattacharya *et al.* 2010; Thabet *et al.* 2021), as evident in the action of nanoparticles like NiNPs, which were synthesized from Ni-hydrazine complexes but showed pesticidal activity that was twice as high as that of the Ni-hydrazine complexes (Rajakumar *et al.* 2013).

Nanobiopesticides are biologically derived chemical complexes with nanoparticles that are intended to be used as pesticides. Nanobiopesticides encompass nanoparticles of either pesticidal active ingredients or other small, engineered structures with useful pesticidal properties (Bergeson 2010; Lade *et al.* 2019). The nano-biopesticides attracted special attention against the insect pests due to their small size, large surface area, high stability, cost-effectiveness, fever toxicity and easy field application (Hazafa *et al.* 2022). Au and Ag nanoparticles from the root of *Acorus calamus* have been reported as good nanobiopesticides (Ganesan and Gurumallesh 2015). Steffy

et al. (2018) reported that Zn, Au and Ag nanoparticles in the fruits and seeds of *Strychnos nux vomica* were nanobiopesticides on white ants. Pyrethrins obtained from the dried flowers of Dalmatian pyrethrum (*Tanacetum cinerariifolium*) constitute a small class of specialized metabolites with insecticidal activities (Copping and Menn 2000). Ryania alkaloid extracts isolated from the stems of *Ryania* spp., particularly *Ryania speciosa*, have insecticidal properties (Copping and Duke 2007).

Nanoscale materials as potential crop preservatives for pre- and post-harvest

Post-harvest loss is one of the problems of agricultural systems and it is a result of the degradation that occurs to the quality and quantity of food production after harvest. In order to practice sustainable agriculture, it is of utmost significance to reduce post-harvest losses in harvested crops to the barest minimum. More than 815 million people, especially in the sub-Saharan region of Africa and south Asia, are recurrently undernourished, while about 22.8 and 14.7% of the populations from these respective regions are malnourished. By 2050, with the projected growth of the world population, it will require at least a 60% increase in food production to meet the population's demand (Stathers *et al.* 2020). Among other ameliorative methods, the application of nanomaterials for the reduction of post-harvest loss in crops has been shown to produce substantial results, as reported in the few accounts available. Nanomaterials in combination with the active ingredients used as pesticides can increase the water solubility potential of such active ingredients, which enhances their penetrability and distribution in order to prevent their untimely degradation. This process can strengthen both the improved uptake and effectiveness of nanopesticides. It also supports the use of a tiny amount, which is an eco-friendly practice. The employability of nanomaterials incorporated into crop matrixes, either directly or indirectly, can improve the shelf life of such crops (Bhuyan *et al.* 2019). Vegetable oils are recently microcapsulized and used in the postharvest preservation of crops; this process involves the employment of active and smart nano-assisted food packages, which are more advantageous than traditional processes (Mihindukulasuriya and Lim 2014). Nanotechnology in crop preservation systems in the form of nanoemulsions, nanoliposomes, edible coatings and other types of nanoparticles has varying benefits (Bhuyan *et al.* 2019). Nanoliposomes have specific antimicrobial potentials (Zou *et al.* 2015) and there have been validated reports on their ability to fuse with bacterial cells and send negatively charged liposomes into the cell matrix, which can ultimately result in endocytosis. Although there are many factors that influence the fusion of the nanoliposomes into the pathogen cell wall (Ma *et al.* 2013; Taherkhani *et al.* 2014).

Nanoemulsions are composed of dissimilar immiscible liquids that are maintained by surfactants like sugar esters, lecithins, polysorbates, *etc*., which are crucial to enhancing crop preservation (Gupta *et al.* 2016). Nanoemulsions of essential oils, such as glycerol monolaurate, are effective against various microorganisms. These formulations, such as Tween 80, Tween 20, dodecane, or pentanol have been used against *Aspergillus niger, Candida albicans* and *Penicillium expansum* (Ram *et al*. 2023). Edible coatings can serve as great carriers of antimicrobial substances, thereby preventing the spread of pathogens right on the external surface of crops (Ottoni *et al.* 2017). Nanoedible coatings have contributed immensely to the postharvest preservation of vegetables and fruits because the direct application of these coatings can control CO_2 and O_2 permeability and reduce loss of moisture and solute oxidation rate without altering both the quality and quantity of the crops (Han 2014; Adiletta *et al.* 2021). All nanocomposites have at one time or another proven their antimicrobial efficacy (Bhuyan *et al.* 2019), but AgNPs have displayed a wide range of beneficial effects for postharvest crop preservation. The toxic effect of AgNPs against different types of microorganisms has been traced to their low volatility and stability at high temperatures (Becaro *et al.* 2015). They are particularly reported as an excellent choice of agent in postharvest preservation mechanisms in view of the fact that they can attach strongly to the microbes and disrupt the cell membrane and DNA, thereby causing cell death (Murphy *et al.* 2015). Another form of nanoparticles with a similar mode of action that can serve as good post-harvest preservative agents in agriculture are TiO_2NPs (Yemmireddy and Hung 2015). whereas further studies are required to establish how NPs interact with crops to improve shelf life and slow down the rate of natural ripening.

Nanomaterials for plant disease management

Plants generally have hyper-accumulation potential and can fixate trace metals, which makes them respond positively to the effects of metallic nanoparticles. Varieties of metallic nanoparticles have been studied and found to deliver improved crop protection potentials (Gupta *et al.* 2023). Different forms of nanoparticles have been tested on different plant disease-causing agents both *in vitro* and *in vivo* and have been found to be effective with little or no ecological carry-over (Ghormade *et al.* 2011). The characteristic effects of nanoscale agricultural materials are quite different from those of similar bulk materials. The solubility and targeted effects of agrochemicals are enhanced when nanomaterials, which are smaller with larger surface areas, are used to convey them at a slower rate to escalate their biological availability (Kah *et al.* 2013; Jenne *et al.* 2018; Gupta *et al*. 2023). In plant protection strategies, different nanoscale formulations have been employed, such as nanofungicides, pesticides, insecticides and herbicides in the form of nanoemulsions, nanoencapsulation, nanoparticles, polymers and inorganic compounds (Kumar

et al. 2019). For nanofungicide formulation, the form that is most effective is the nano emulsion because it is smaller in size, lower in viscosity and highly stable (Chuan *et al.* 2013; Das *et al.* 2021). Research has shown that out of the different forms of nanomaterials available, nanoparticles are mostly utilized in the agricultural system, especially for protection against plant infections.

The activities of nanoparticles in the management of crop diseases can be as a result of direct application, as carriers of another or other disease protection agents, or as nanodevices for disease detection and diagnosis (Worrall *et al.* 2018). Nanoparticles in their nanoforms have superior interactions with plant pathogens due to their small sizes compared with their macroform structure, which is large (Das *et al.* 2021). Nanoparticles also exhibit their antibacterial property against different antibiotic-resistant bacteria by engaging the bacterial cell wall, thereby taking control of microbial activity (Wang *et al.* 2017a, b, c). There was also a novel investigation into the application of nanoparticles as control agents for plant pests and pathogens. In this research, the control of the activity and spread of *Sitophilus oryzae* and the baculovirus BmNPV (*Bombyx mori* nuclear polyhedrosis virus), which attacks silkworms, has been investigated and reported. The bioassay involved the formulation of solid and liquid nanoparticles, which were applied directly to rice and stored together with 20 adult *S. oryzae*. The experiment resulted in a significant decrease in the viral load in the suspension of hydrophobic alumino-silicate nanoparticles.

Other types of nanoparticles have been successfully applied as crop protection agents to manage various crop diseases. For instance, AgNPs have been reported to suppress the spread of soil fungal pathogens like *Phytophthora parasitica*, *Meloidogyne* spp. and *Fusarium* spp. *etc.* so as to avoid resultant crop penetration (Banerjee *et al.* 2021). Other applications of AgNPs for crop protection include increased disease resistance potential in *Arabidopsis thaliana* against *Pseudomonas syringae*, increased (70%) disease suppression potential of banana fruits against *Colletotrichum musae*, enhanced antifungal potential in combination with fluconazole against *Cladosporium berbarum, Alternaria alternata* and *Fusarium oxysporum*, and disease control effect in tomatoes against *Xanthomonas perforans* (Ocsoy *et al.* 2013; Jagana *et al.* 2017; Fajar *et al.* 2020; Banerjee *et al.* 2021). Nanoparticles of Zinc (ZnNPs), on the other hand, have shown substantive crop protection effects over a range of pre- or post-harvest crop diseases, including mucor rot, black rot, fusarium wilt, blossom blight, root rot, damping off, wire stem and Rhizopus soft rot. They are reported to exhibit strong antimicrobial activity against the following pathogens: *Mucor plumbeus*, *Alternaria alternata, Fusarium oxysporum, Sclerotinia sclerotiorum, Rhizoctonia solani* and *Rhizopus stolonifera* (Graham *et al.* 2016; Sardella *et al.* 2017; Banerjee *et al.* 2021).

Nanoparticles of copper (CuNPs) have manifested fungistatic, bacteriostatic and anti-nematodal potentials against some pathogens like *Phytophthora infestans, Streptomyces griseus* and *Xiphinema index*, thereby delivering favorable protective effects, particularly to tomato, tea and grapes, respectively (Elmer and White 2018; Sarkar *et al.* 2020; Banerjee *et al.* 2021). Among the non-metallic nanoparticles studied, sulfur nanoparticles (SNPs) and titanium nanoparticles (TiNPs) are the most studied. SNPs have been used as a crop pathogen disease control agent against *Fusarium solani*, *F. oxysporum, Aspergillus niger* and *Venturia inaequalis*, while TiNPs have proven to be a potential antifungal agent (Rao and Paria 2013; Boxi *et al.* 2016). Other metallic nanoparticles like MnONPs and SiNPs have exhibited antifungal effects against the pathogen responsible for wilt diseases in egg plants, watermelon and powdery mildew, respectively (Elmer and White 2018; Banerjee *et al.* 2021). Graphene oxide, a type of carbon nanoparticle, has been reported to express about 95% antibacterial resistance against *Xanthomonas oryzae* (Chen *et al.* 2013). Copper nanoparticles (CuNPs) were able to assist in the control of bacterial blight on rice and leaf spot disease in mung beans. There is currently no documented report about the antimicrobial efficacy of silica itself, but silica nanoparticles (SiNPs) have also reportedly been of help to plants by activating enhanced physiological mechanisms and consequent resistance to various diseases. Iron NPs are good agents against fungal cell growth and development by reducing the permeability potential of the cell, which can eventually result in cell death. Zinc NPs, when in solution, release the radical's hydroxyl and superoxide to prevent fungal conidiogenesis (Das *et al.* 2021).

Application of Nanoparticles for Crop Protection Mechanism

With the increase in climate change, agricultural systems all over the world are burdened with many problems; the urgency to attain food security, improved production of crops and sustainability necessitates the use and application of nanotechnology to achieve this (Shang *et al.* 2019). It is a recent means employed for research in agriculture that basically centers on the diagnosis of plants, increasing productivity and improving new disease-resistant varieties of plants (Banerjee *et al.* 2021).

Crop preservation methods using nanotechnology through the use of nanoparticles have the potential to: affect disease tolerance; increase crop yield; aid in the fast diagnosis of plant diseases and be cost-effective (Banerjee *et al.* 2021). Nanoparticles Green synthesis, employing the use of plants and other diverse microorganisms, has over time drawn special interest amongst scientists as it is less expensive, yields good results and is eco-friendly and minimalist (Banerjee *et al.* 2021). It is a reassuring tool for the development of nanopesticides, nanoinsecticides and nanofertilizers that reduce harmful environmental pollutants

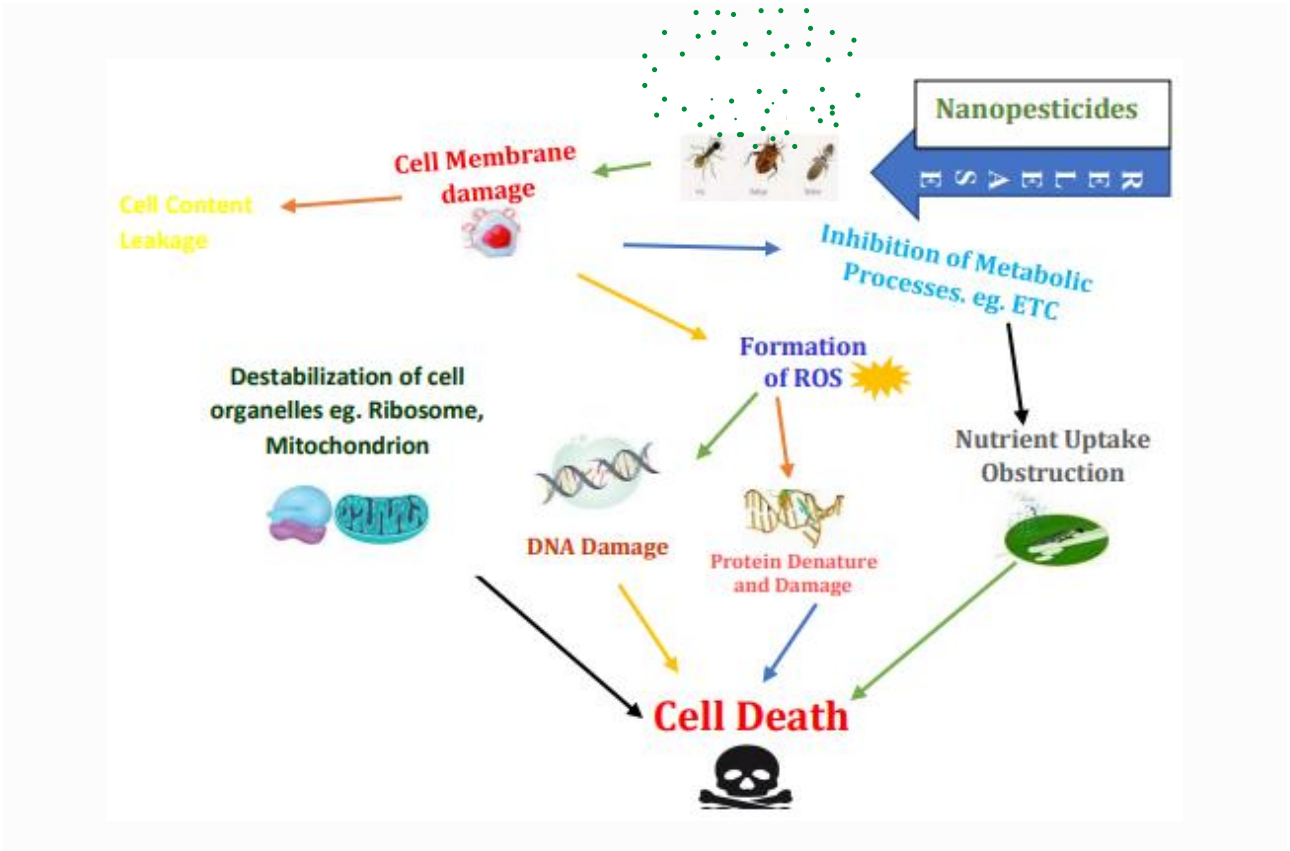


Fig. 3: The mechanism of action of nanopesticides on target pest cells

in recyclables and agricultural fields (Ghidan *et al.* 2017; Shang *et al.* 2019; Banerjee *et al.* 2021). Studies by Hoang *et al.* (2022) stated that the use of metal nanoparticles prior to sowing treatment resulted in wheat and barley having a positive modification in their morphometric parameters; a statistically significant reduction was noticed in the development of the phytopathogenic fungus *Alternaria* sp. employing nanoparticles of chitosan-Ag (at 15 and 30 mg kg^{-1}), CoO (at 0.4 and 0.5 mg kg^{-1}), CuO and ZnO (both at 0.5 mg kg^{-1}). A study by Elmer and White (2018) showed that *Fusarium* spp., *Phytophthora parasitica* and *Meloidogyne* spp. were suppressed using silver nanoparticles.

Nanosensors, an application of nanoparticles in agriculture, aid in the quantification and monitoring of the production of crops, the management of disease-affecting crops, insect attacks and environmental pollutants (El-Shanshoury *et al.* 2020; Banerjee *et al.* 2021). Keshvadi *et al.* (2019) stated that silver nanoparticle (AgNP) nanoparticle, which is significantly well-researched, is mostly incorporated in the agricultural field for the control of plant pathogens with a significant impact on antimicrobial activities. According to Banerjee *et al.* (2021), the use of nanoparticles has a direct impact on the physiology of crops through the application of nanofertilizer, which enhances the ability of plants to absorb nutrients and regulates their development, germination of seeds and acclimatization. The use of nano-pesticides increases crop fertility by boosting the mobility potential of the pesticides and in plant pathology, nanoparticles such as metals and metal oxides, non-metal carbon nanoparticles and chitosan nanoparticles have been employed to control diverse plant pathogens (Banerjee *et al.* 2021). Nano SiO_2, TiO_2 and Zeolite use positively stimulated the germination of seeds in crop plants (Manjaiah *et al.* 2019).

Nanoparticle use in foliar sprays can be employed to help prevent pathogens and also aid plant development (Das *et al.* 2021). Using silver, copper and silicon nanoparticles, an increase in crop growth was observed (Ahmad *et al.* 2020; Khan *et al.* 2021; Hoang *et al.* 2022). Nanoparticles as potential crop protection agents against various pathogens could be applied directly or in combination with other potential antimicrobial substances. The mechanism of action is particularly active against pathogens by causing the plasmolysis of the fungal hyphae, leading to irreparable damage to the cell walls and the prevention of proper operation of the plasma membrane. They can also damage the DNA, disrupt the electron transport chain or protein oxidation, obstruct nutrient uptake and cause subsequent death (Fig. 3) as reported by (Das *et al.* 2021). Nanoparticles have been tested and applied at different environmental conditions and concentrations with varying degrees of effectiveness for protection against crop pests (Table 1).

Table 1: The nanoparticles tested for crop protection potential against pests and their applications

Nanoparticle	Susceptible Organism	Tested Concentration and Mode of Application	Effect	References
SiNPs	*Sitophilus oryzae* (Weevil)	Dry direct application to grains @ 0.5 and 1 g kg^{-1} of NP/grain	Increased weevil mortality	Debnath *et al.* (2011)
SNPs	*Aspergillus niger*	In vitro wet application @125-2000 ppm	Dose-dependent fungal inhibitory effect	Choudhury *et al.* (2012)
SNPs	*Rhizopus oryzae* *Penicillium italicum*	Fruit inoculation	Dose-dependent microbicidal effect	Fu *et al.* (2014)
AuNPs	*Aspergillus flavus* *Fusarium oxysporum* *Escherichia coli* *Staphylococcus aureus* *Salmonella typhi*	*In vitro* application and Minimum Inhibitory Concentration @ 0.34 mg mL^{-1}	Antimicrobial effects	Chidambaram *et al.* (2013); Smitha and Gopchandran (2013) Lokina *et al.* (2014)
AgNPs	*Hippobosca maculate* (hematophagous flies) *Rhipicephalus microplus* (cattle ticks)	Wet application of particles @5-25 mg L^{-1} and 2-10 mg L^{-1}	Insecticidal effects on adult insect	Pestovsky and Martínez-Antonio (2017)
	Alternaria alternata *Botrytis cinerea* *Curvularia lunata*	Wet application @ 1.25-20 mg L^{-1}	Death of larvae	Pestovsky and Martínez-Antonio (2017)
	Colletotrichum coccodes *Monilinia* sp. *Pyricularia* sp. *Fusarium oxysporum*	5-15 mg $plate^{-1}$	Microbial inhibitory effect	Fernández *et al.* (2016)
	Phytophtora infestans *Phytophtora capsica*	*In vitro* application @ 2 m*M* and 4 m*M*	Antifungal effect	Velmurugan *et al.* (2017)
	Aspergillus flavus	*In vitro* application @ 2 mmol L^{-1}	Hyphal growth inhibitory effect	Yao *et al.* (2020)
	Penicillium vulpinum	10-30 μg $plate^{-1}$	Growth inhibitory effect	Velmurugan *et al.* (2015)
	Pseudomonas aeruginosa	*In vitro* application @ 70-800 or 60-800 μg mL^{-1} *In vitro* application @ 5 m*M*	Antifungal activity Antibacterial effect	Ismaiel and Tharwat (2014) Femi-Adepoju *et al.* (2019)
Ag_2O/Ag	*Aspergillus niger* *Aspergillus flavus* *Aspergillus fumigatus*	*In vitro* application @ 50 mg L^{-1}	Growth suppression effect	Thenmozhi *et al.* (2013)
Ag_3O_4	*Aspergillus niger* *Pseudomonas aeruginosa*	*In vitro* application @ 10-50 μg $plate^{-1}$	Toxicity effect	Suresh *et al.* (2016)
NiNPs	*Rhipicephalus microplus* (Cattle tick larvae) *Hyalomma annatolicum*	*In vitro* application @ I5-10 mg L^{-1}	Anti-larval effect	Latvala *et al.* (2016)
PtNPs	*Colletotrichum acutatum* *Cladosporium fulvum*	2, 4 and 8 μg $plate^{-1}$	Antifungal activity	Velmurugan *et al.* (2016)
CuNPs	*Alternaria alternata* *Aspergillus flavus* *Fusarium solani*	Plate dilution method @ 20-100 mg L^{-1}	Dose-dependent and species dependent antifungal activity	Pestovsky and Martínez-Antonio (2017)
	Alternaria alternata *Curvularia lunata* *Fusarium oxysporum* *Phoma destructiva*	*In vitro* paper disc diffusion @ 20 μg/disc	Fungicidal activity	Pestovsky and Martínez-Antonio (2017)
CuONPs	*Pythium* spp.	Field spraying @ 50-500 mg L^{-1}	Growth inhibitory effect	Zabrieski *et al.* (2015)
ZnONPs	*Aspergillus flavus* *Aspergillus niger* *Aspergillus fumigatus* *Fusarium culmorum* *Fusarium oxysporum*	In vitro application @ 50 μg mL^{-1}	Antifungal	Rajiv *et al.* (2013)
	Aspergillus flavus *Aspergillus niger* *P. aeruginosa*	*In vitro* application @ 2-3 μg mL^{-1}	Microbial inhibitory effect	Pestovsky and Martínez-Antonio (2017)
	Pythium spp. *Botrytis cinerea*	Wet spraying on crops @ 100 mg L^{-1}	Antifungal effect	Zabrieski *et al.* (2015)
	Penicillium expansum	*In vitro* application @ 3-12 m*M*	Antibacterial effect	Pestovsky and Martínez-Antonio (2017)
ZnO@SiO_2NPs	*Aspergillus niger* *Fusarium oxysporum*	*In vivo* application @ 500-4000 ppm	Target specific antifungal effect	Mitra *et al.* (2015)
Fe_3O_4/ZnO/AgBr Nano composite (1:2-1:10)	*Fusarium graminearum* *Fusarium oxysporum*	Plate dillution @ 3.33-26.66 ppm	Fungal sporulation inhibitory effect	Hoseinzadeh *et al.* (2016)
TiO_2NPs	*Rhipicephalus microplus* *Haemaphysalis bispinosa*	Wet spraying @ 4-20 mg L^{-1}	Increased insect mortality effect	Marimuthu *et al.* (2013)
Reduced Graphene Oxide Nano sheets	*Fusarium oxysporum* *Aspergillus niger*	*In vitro* application @ 1-500 ug mL^{-1}	Dose -dependent and species dependent antifungal effect	Pestovsky and Martínez-Antonio (2017)
Chitosan	*Fusarium graminearum* *Aspergillus parasiticus*	*In vitro* application @ 100-5000 ppm *In vitro* application @ 5.10^{-3}/agar plate	Antifungal effect Antifungal effect	Kheiri *et al.* 2016 Cota-Arriola *et al.* (2013)
Cu-chitosan NPs	*Alternaria solani* *Fusarium oxysporum*	*In vitro* and *in vivo* application @ 0.08-0.12% of NPs	Dose dependent antifungal activity	Saharan *et al.* (2015)

Conclusion

The application of nanoparticles is easy, durable, non-toxic to plants and they have a larger surface area, which makes them distinguished materials to be used as preservative components. It is expected that in the years to come, the development of nanostructured boosters will increase the efficiency of biological pesticides and insecticides with reduced doses. The green method of nanoparticle fabrication is being widely studied and applied to investigate the extent of its potential in crop protection and preservation. This technology has shown great promise in food processing, food packaging, crop yield, crop improvement and post-harvest preservation. Nanotechnology can be responsible for the provision of better-quality food by encouraging precision farming, especially with the focus on protecting crops from a wide range of pathogens. The capabilities of metallic nanoparticles to get rid of targeted microbes from crops have dramatically reduced the use of agrochemicals. The application can be either direct or indirect, as an integrated substance in a fungicide or pesticide formulation. The mode of action of nanoparticles is precise and diverse, but they exert concerted effects on their targets. They relate directly to target cells and organelles and can have an adverse effect on target pest and insect cells but remain non-toxic to non-target entities. The use of nanoparticle-based pesticides offers long-lasting protection to crops and enhances the solubility of active components that are either insoluble or partially soluble.

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Author Contributions

While other authors equally contributed by proposing distinct areas of contribution, the primary author assembled and edited the review piece. Before submission, AEA reviewed the article.

Conflict of Interest

All authors declare no conflict of interest.

Data Availability

Data presented in this study will be available on a fair request to the corresponding.

Ethics Approvals

This study do not require any human or animal ethical approval, however, all authors declare their informed consent to be a part of this review. All information contained in this review are properly cited following standard procedure.

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References

Adiletta G, MD Matteo, M Petriccione (2021). Multifunctional role of chitosan edible coatings on antioxidant systems in fruit crops: A review. *Intl J Mol Sci* 22:2633

Ahmad B, MMA Khan, H Jaleel, A Shabbir, Y Sadiq, M Uddin (2020). Silicon nanoparticles mediated increase in glandular trichomes and regulation of photosynthetic and quality attributes in *Mentha piperita* L. *J Plant Growth Regul* 57:339–346

Asif M, S Islam, AM Malik, ZZ Dar, A Masood, S Shafi, B Rashid, S Sidique (2022). Nano Pesticides application in agriculture and their impact on environment. agricultural development in Asia – Potential use of nano-materials and nano-technology. In: *Agricultural Development in Asia-Potential Use of Nano-Materials and Nano-Technology*, Chapter 3. Asaduzzaman M, M Afroz (Eds.). *Intechopen*, London

Ayesha M, AB Muhammad, MH Maaz (2020). Nanoparticles as a preservative solution can enhance postharvest attributes of cut flowers. *Italus Hortus* 27:1–14

Banerjee A, A Sarkar, K Acharya, N Chakraborty (2021). Nanotechnology: An emerging hope in crop improvement. *Lett Appl Nanobiosci* 10:2784–2803

Becaro AA, FC Puti, DS Correa, EC Paris, JM Marconcini, MD Ferreira (2015). Polyethylene films containing silver nanoparticles for applications in food packaging: Characterization of physicochemical and anti-microbial properties. *J Nanosci Nanotechnol* 15:2148–2156

Bergeson LL (2010). Nanosilver: US EPA's pesticide office considers how best to proceed. *Environ Qual Manage* 19:79–85

Bhattacharya A, A Bhaumik, U Pathipati, S Mandel, TT Epidi (2010). Nano-particles: A recent approach to insect pest control. *Afr J Biotechnol* 9:3489–3493

Bhuyan D, GW Greene, RK Ratul (2019). Prospects and application of nanobiotechnology in food preservation: Molecular perspectives. *Crit Rev Biotechnol* 39:759–778

Boxi SS, K Mukherjee, S Paria (2016). Ag doped hollow TiO_2 nanoparticles as an effective green fungicide against *Fusarium solani* and *Venturia inaequalis* phytopathogens. *Nanotechnology* 27:085103

Chen J, X Wang, H Han (2013). A new function of graphene oxide emerges: Inactivating phytopathogenic bacterium, *Xanthomonas oryzae* pv. *oryzae*. *J Nanopart Res* 15:1–14

Chen X, Y Chen, L Zou, X Zhang, Y Dong, J Tang DJ McClements, W Liu (2019). Plant-based nanoparticles prepared from proteins and phospholipids consisting of a core–multilayer-shell structure: Fabrication, stability and foamability. *J Agric Food Chem* 67:6574–6584

Chidambaram J, R Rajendiran, R Abdul, P Pachiappan (2013). Green synthesis of gold nanoparticles using seed aqueous extract of *Abelmoschus esculentus* and its antifungal activity. *Ind Crops Prod* 45:423–429

Choudhury SR, M Ghosh, A Goswami (2012). Inhibitory effects of sulfur nanoparticles on membrane lipids of *Aspergillus niger*: A novel route of fungistasis. *Curr Microbiol* 65:91–97

Chuan L, P He, MF Pampolino, AM Johnston, J Jin, X Xu, W Zhou (2013). Establishing a scientific basis for fertilizer recommendations for wheat in China: Yield response and agronomic efficiency. *Field Crops Res* 140:1–8

Copping LG, JJ Menn (2000). Biopesticides: A review of their action, applications and efficacy. *Pest Manage Sci* 56:651–676

Copping LG, SO Duke (2007). Natural products that have been used commercially as crop protection agents. *Pest Manage Sci* 63:524–554

Cota-Arriola O, MO Cortez-Rocha, JM Ezquerra-Brauer, J Lizardi-Mendoza, A Burgos-Hernández, RM Robles-Sánchez, M Plascencia-Jatomea (2013). Ultrastructural, morphological and antifungal properties of micro and nanoparticles of chitosan crosslinked with sodium tripolyphosphate. *J Polym Environ* 21:971–980

Dada AO, AA Inyinbor, IE Idu, OM Bello, AP Oluyori, TA Adelani-Akande, AA Okunola, O Dada (2018). Effect of operational parameters, characterization and antibacterial studies of green synthesis of silver nanoparticles, using *Tithonia diversifolia*. *Peer J* 6:e5865

Das K, P Kanti Jhan, S Chandra Das, FM Aminuzzaman, B Yaw Ayim (2021). Nanotechnology: Past, present and future prospects in crop protection. technology in agriculture. *Technol Agric* 2021:1–22

Debnath N, S Das, D Seth, R Chandra, SC bhatacharya, A Goswami (2011). Entomotoxic effect of silica nanoparticles against *Sitophilus oryzae* L. *J Pest Sci* 84:99–105

Elmer W, JC White (2018). The future of nanotechnology in plant pathology. *Annu Rev Phytopathol* 56:111–133

El-Shanshoury AER, OM Darwesh, SZ Sabae, OA Awadallah, SH Hassan (2020). Bio-manufacturing of Selenium nanoparticles by *Bacillus subtilis* isolated from Qarun lake and evaluation their activity for water remediation. *Biointerf Res Appl Chem* 10:5834–5842

Fajar MN, E Endarko, A Rubiyanto, NANN Malek, T Hadibarata, A Syafiuddin (2020). A green deposition method of silver nanoparticles on textiles and their antifungal activity. *Biointerf Res Appl Chem* 10:4902–4907

Femi-Adepoju AG, AO Dada, KO Otun, AO Adepoju, OP Fatoba (2019). Green Synthesis of silver nanoparticles using terrestrial fern (*Gleichenia pectinata* (Willd.) C. Presl.): Characterization and antimicrobial studies. *Heliyon* 5:e01543

Femi-Adepoju AG, AO Adepoju, PO Fatoba, VT Olayemi (2018). Biosynthesis, characterization and antimicrobial potency of silver nanoparticles fabricated from *Phymatode scolopendria* (Burm. f.) ching. *Intl J Curr Res* 10:76229–76233

Fernández JG, MA Fernández-Baldo, E Berni, G Camí, N Durán, J Raba, MI Sanz (2016). Production of silver nanoparticles using yeasts and evaluation of their antifungal activity against phytopathogenic fungi. *Proc Biochem* 51:1306–1313

Fu LH, KD Hu, LY Hu, YH Li, LB Hu, H Yan, YS Liu, H Zhang (2014). An antifungal role of hydrogen sulfide on the postharvest pathogens *Aspergillus niger* and *Penicillium italicum*. *PLoS One* 9:e104206

Ganesan RM, PH Gurumallesh (2015). Synthesis of gold nanoparticles using herbal Acorus calamus rhizome extract and coating on cotton fabric for antibacterial and UV blocking applications. *Arab J Chem* 12:2166–2174

Gangwar J, SJ Kadanthottu, JJ Puthukulangara, JT Kurian (2023). Nano-technological interventions in crop production-A review. *Physiol Mol Biol Plants* 29:93–107

Garg R, S Gonuguntla, SK Saddam, SM Iqbal, AO Dada, P Ujjwal, A Mohsen (2024). Sputtering thin films: Materials, applications, challenges and future directions., *Adv Colloid Interf Sci* 330:103203

Gatea EA, AAA Hamdan, IAA Hamdan (2022). Synthesis of nanoparticles: A review. *Kerbal J Pharm Sci* 1:259–271

Ghidan AY, TMA Antary (2019). Applications of nanotechnology in agriculture. *In: Applications of Nanobiotechnology*, pp:1–13. Stoytcheva M, R Zlatev (Eds.). IntechOpen, London

Ghidan AY, TM Al-Antary, AM Awwad (2017). Aphidicidal potential of green synthesized magnesium hydroxide nanoparticles using *Olea europaea* leaves extract. *ARPN J Agric Biol Sci* 12:293–301

Ghormade V, MV Deshpande, KM Paknikar (2011). Perspectives for nano-biotechnology enabled protection and nutrition of plants. *Biotechnol Adv* 29:792–803

Graham JH, EG Johnson, ME Myers, M Young, P Rajasekaran, S Das, S Santra (2016). Potential of nanoformulated zinc oxide for control of citrus canker on grapefruit trees. *Plant Dis* 100:2442–2447

Guleria G, S Thakur, M Shandilya, S Sharma, S Thakur, S Kalia (2023). Nanotechnology for sustainable agro-food systems: The need and role of nanoparticles in protecting plants and improving crop productivity. *Plant Physiol Biochem* 194:533–549

Gupta A, F Rayeen, R Mishra, M Tripathi, N Pathak (2023). Nanotechnology applications in sustainable agriculture: An emerging eco-friendly approach. *Plant Nano Biol* 4:100033

Gupta A, HB Eral, TA Hatton, PS Doyle (2016). Nanoemulsions: Formation, properties and applications. *Soft Matter* 12:2826–2841

Hamel D, V Rozman, A Liška (2020). Storage of Cereals in Warehouses with or without pesticides. *Insects* 11:846-866

Han JH (2014). Edible films and coatings: A review. *Innov Food Pack* 9:213–55

Hazafa A, M Murad, MU Masood, S Bilal, MN Khan, Q Farooq, MO Iqbal, M Shakir, M Naeem (2022). Nano-Biopesticides as an emerging technology for pest management. In: *Insecticides – Impact and Benefits of Its Use for Humanity*, Chapter 21. Rebolledo Ranz RE (Ed.). *Intechopen*, London

Hoang AS, HH Cong, VP Shukanov, LA Karytsko, SN Poljanskaja, VE Melnikava, AI Mashkin, HT Nguyen, KD Pham, MC Phan (2022). Evaluation of metal nano-particles as growth promoters and fungi inhibitors for cereal crops. *Chem Biol Technol Agric* 9:12

Hoseinzadeh A, A Habibi-Yangjeh, M Davari (2016). Antifungal activity of magnetically separable Fe_3O_4/ZnO/AgBr nanocomposites prepared by a facile microwave-assisted method. *Progr Nat Sci* 26:334–340

Huang SW, L Wang, LM Liu, Q Fu, DF Zhu (2014) Nonchemical pest control in China rice: A review. *Agron Sustain Dev* 34:275–291

Ibrahim K, S Khalid, K Idrees (2019). Nanoparticles: Properties, applications and toxicities. *Arab J Chem* 12:908–931

Ismaiel AA, NA Tharwat (2014). Antifungal activity of silver ion on ultrastructure and production of aflatoxin B1 and patulin by two mycotoxigenic strains, *Aspergillus flavus* OC1 and *Penicillium vulpinum* CM1. *J Mycol Méd* 24:193–204

Jagana D, YR Hegde, R Lella (2017). Green nanoparticles: A novel approach for the management of banana anthracnose caused by *Colletotrichum musae*. *Intl J Curr Microbiol Appl Sci* 6:1749–1756

Jenne M, M Kambham, NP Tollamadugu, HP Karanam, MK Tirupati, RR Balam, S Shameer, M Yagireddy (2018). The use of slow releasing nanoparticle encapsulated azadirachtin formulations for the management of *Caryedon serratus* (groundnut Bruchid). *IET Nanobiotechnol* 12:963–967

Kah M, S Beulke, K Tiede, T Hofmann (2013). Nano pesticides: State of knowledge, environmental fate and exposure modeling. *Crit Rev Environ Sci Technol* 43:1823–1867

Keshvadi M, F Karimi, S Valizadeh, A Valizadeh (2019). Comparative study of antibacterial inhibitory effect of silver nanoparticles and garlic oil nanoemulsion with their combination. *Biointerf Res Appl Chem* 9:4560–4566

Khan J, J Chandra, R Xalxo, J Korram, ML Satnami, S Keshavkant (2021). Amelioration of ageing associated alterations and oxidative inequity in seeds of *Cicer arietinum* by silver nanoparticles. *J Plant Growth Regul* 40:1341–1351

Kheiri A, SAM Jorf, A Malihipour, H Saremi, M Nikkhah (2016). Application of chitosan and chitosan nanoparticles for the control of Fusarium head blight of wheat (*Fusarium graminearum*) *in vitro* and greenhouse. *Intl J Biol Macromol* 93:1261–1272

Krishnamurthy S, M Veerasamy, G Karruppaya (2020). A review on plant sources for nano biopesticide production. *Lett Appl NanoBioSci* 9:1348–1358

Kumar S, M Nehra, N Dilbaghi, G Marrazza, AA Hassan, KH Kim (2019). Nano-based smart pesticide formulations: Emerging opportunities for agriculture. *J Cont Release* 294:131–153

Kumar S, M Nehra, D Kedia, N Dilbaghi, K Tankeshwar, KH Kim (2018). Carbon nanotubes: A potential material for energy conversion and storage. *Prog Ener Combust Sci* 64:219–253

Lade BD, DP Gogle, DB Lade, GM Moon, SB Nandeshwar, SD Kumbhare (2019). Nanobiopesticide formulations: Application strategies today and future perspectives. In: *Nano-biopesticides today and future perspectives*, pp:179-206. Koul O (Ed.). Academic Press, London

Latvala S, J Hedberg, SD Bucchianico, L Möller, IO Wallinder, K Elihn, H Karlsson (2016). Nickel release, ROS generation and toxicity of Ni and NiO micro- and nanoparticles. *PLoS One* 11:e0159684

Lokina S, R Suresh, K Giribabu A Stephen, RL Sundaram, V Narayanan (2014). Spectroscopic investigations, antimicrobial and cytotoxic activity of green synthesized gold nanoparticles. *Spectrochim Acta A Mol Biomol Spectrosc* 14:84–90

Ma Y, Z Wang, W Zhao, T Lu, R Wang, Q Mei, T Chen (2013). Enhanced bactericidal potency of nanoliposomes by modification of the fusion activity between liposomes and bacterium. *Intl J Nanomed* 8:2351–2360

Maity A, R Belgamwar, V Polshettiwar (2019). Facile synthesis to tune size, textural properties and fiber density of dendritic fibrous nanosilica for applications in catalysis and CO_2 capture. *Nat Protoc* 14:2177–2204

Manjaiah KM, R Mukhopadhyay, R Paul, SC Datta, P Kumararaja, B Sarkar (2019) Clay minerals and zeolites for environmentally sustainable agriculture. *In: Modified Clay and Zeolite Nanocomposite Materials*, pp:309–329. Mariano M, S Binoy, L Alessio (Eds.). Elsevier: Amsterdam, The Netherlands

Marimuthu S, AA Rahuman, C Jayaseelan, AV Kirthi, T Santhoshkumar, K Velayutham, A Bagavan, C Kamaraj, G Elango, M Iyappan, C Siva, L Karthik, KVB Rao (2013). Acaricidal activity of synthesized titanium dioxide nanoparticles using Calotropis gigantean against *Rhipicephalus microplus* and *Haemaphysalis bispinosa*. *Asian Pac J Trop Med* 6:682–688

Mathew IL, D Singh, R Singh, C Tripathi (2014). *Bacillus thuringiensis*: The biocontrol agent in a food web perspective. *Biolife* 2:348–362

Mihindukulasuriya SDF, LT Lim (2014). Nanotechnology development in food packaging: A review. *Trends Food Sci Technol* 40:149–167

Mitra S, P Patra, S Pradhan, N Debnath, KK Dey, S Sarkar, D Chattopadhyay, A Goswami (2015). Microwave synthesis of ZnO@mSiO_2 for detailed antifungal mode of action study: Understanding the insights into oxidative stress. *J Colloid Interf Sci* 444:97–108

Murphy CJ, AM Vartanian, FM Geiger, RJ Hamers, J Pedersen, Q Cui, ZE Rosenzweig (2015). Biological responses to engineered nanomaterials: Needs for the next decade. *ACS Ctr Sci* 1:117–123

Ocsoy I, ML Paret, MA Ocsoy, S Kunwar, T Chen, M You, W Tan (2013). Nanotechnology in plant disease management: DNA-directed silver nanoparticles on graphene oxide as an antibacterial against *Xanthomonas perforans*. *ACS Nano* 7:8972–8980

Oluwasogo DA, S Varangane, YT Prabhu, BM Abraham, V Perupogu, U Pal (2023). Biosynthetic modulation of carbon-doped ZnO for rapid photocatalytic endocrine disruptive remediation and hydrogen evolution. *J Clean Prod* 394:136393

Ottoni CA, MF Simões, S Fernandes, JG Dos Santos, ESD Silva, RFBD Souza, AE Maiorano (2017). Screening of filamentous fungi for antimicrobial silver nanoparticles synthesis. *AMB Express* 7:31

Pestovsky YS, A Martínez-Antonio (2017). The use of nanoparticles and nanoformulations in agriculture. *J Nanosci Nanotechnol* 17:8699–8730

Qu M, H Merzendorfer, B Moussian, Q Yang (2022). Bioinsecticides as future mainstream pest control agents: Opportunities and challenges. *Front Agric Sci Eng* 9:82–97

Quoc HP, L Dusan, O Kostya, TN Nghiep, H Volker (2020). Perspectives on plasma-assisted synthesis of N-doped nanoparticles as nano pesticides for pest control in crops. *React Chem Eng* 8:1374–1396

Rajakumar G, AA Rahuman, K Velayutham, J Ramyadevi, K Jeyasubramanian, A Marikani, G Elango, C Kamaraj, T Santhoshkumar, S Marimuthu, AA Zahir, A Bagavan, C Jayaseelan, AV Kirthi, M Iyappan, C Siva (2013). Novel and simple approach using synthesized nickel nanoparticles to control blood-sucking parasites. *Vet Parasitol* 191:332–339

Rajiv P, S Rajeshwar, R Venckatesh (2013). Bio-fabrication of zinc oxide nanoparticles using leaf extract of *Parthenium hysterophorus* L. and its size-dependent antifungal activity against plant fungal pathogens. *Spectrochim Acta A Mol Biomol Spectrosc* 112:384–387

Ram AKM, R Singh, M Rana, SA Dwivedi, K Parmar, A Sharma, C Kumar, V Pandey, V Kumar, S Mishra, A Tomar (2023). Nanobiotechnology: Synthesis components and a few approaches for controlling plant diseases. *Plant Nano Biol* 4:100038

Rao KJ, S Paria (2013). Use of sulfur nanoparticles as a green pesticide on *Fusarium solani* and *Venturia inaequalis* phytopathogens. *RSC Adv* 3:10471–10478

Saharan V, G Sharma, M Yadav, MK Choudhary, SS Sharma, A Pal, R Raliya, P Biswas (2015). Synthesis and *in vitro* antifungal efficacy of Cu-chitosan nanoparticles against pathogenic fungi of tomato. *Intl J Biol Macromol* 75:346–353

Sardella D, R Gatt, VP Valdramidis (2017). Physiological effects and mode of action of ZnO nanoparticles against postharvest fungal contaminants. *Food Res Intl* 101:274–279

Sarkar J, N Chakraborty, A Chatterjee, A Bhattacharjee, D Dasgupta, K Acharya (2020). Green Synthesized copper oxide nanoparticles ameliorate defence and antioxidant enzymes in *Lens culinaris*. *Nanomaterials* 10:312

Singh S, A Kumar, P Arora, S Sahu (2019). Nano technology and its applications in crop improvement. *Bull Environ Pharmacol Life Sci* 8:1–6

Shang Y, MK Hasan, GJ Ahammed, M Li, H Yin, J Zhou (2019). Applications of nanotechnology in plant growth and crop protection: A review. *Molecules* 24:2558

Singh A, N Dhiman, AK Kar, D Singh, MP Purohit, D Ghosh, S Patnaik (2020). Advances in controlled release pesticide formulations: Prospects to safer integrated pest management and sustainable agriculture. *J Hazard Mater* 385:121525

Singh H, A Sharma, SK Bhardwaj, SK Arya, N Bhardwaj, M Khatri (2021). Recent advances in the applications of nano-agrochemicals for sustainable agricultural development. *Environ Sci Proc Impacts* 23:213–239

Smitha SL, KG Gopchandran (2013) Surface Enhanced Raman Scattering, Antibacterial and antifungal active triangular gold nanoparticles. *Spectrochim Acta A Mol Biomol Spectrosc* 102:114–119

Stathers T, D Holcroft, L Kitinoja, BM Mvumi, A English, O Omotilewa, M Kocher, J Ault, M Torero (2020). A scoping review of interventions for crop postharvest loss reduction in Sub-Saharan Africa and South Asia. *Nat Sustain* 3:821–835

Steffy K, G Shanthi, AS Maroky, S Selvakumar (2018). Synthesis and characterization of ZnO phytonanocomposite using *Strychnos nux-vomica* L. (Loganiaceae) and antimicrobial activity against multidrug-resistant bacterial strains from diabetic foot ulcer. *J Adv Res* 9:69–77

Suresh S, S Karthikeyan, P Saravanan, K Jayamoorthy, KI Dhanalekshmi (2016). Comparison of antibacterial and antifungal activity of 5-amino-2-mercapto benzimidazole and functionalized Ag_3O_4 nanoparticles. *Karbal Intl J Mod Sci* 2:129–137

Taherkhani S, M Mohammadi, J Daoud, S Martel, M Tabrizian (2014). Covalent binding of nanoliposomes to the surface of magnetotactic bacteria for the synthesis of self-propelled therapeutic agents. *ACS Nano* 8:5049–5060

Thabet AF, HA Boraei, OA Galal, MFM El-Samahy, KM Mousa, YZ Zhang, M Tuda, EA Helmy, J Wen, T Nozaki (2021). Silica nanoparticles as pesticide against insects of different feeding types and their non-target attraction of predators. *Sci Rep* 11:14484

Thenmozhi M, K Kannabiran, R Kumar, VG Khanna (2013). Antifungal activity of *Streptomyces* sp. VITSTK7 and its synthesized Ag_2O/Ag nanoparticles against medically important *Aspergillus* pathogens. *J Mycol Med* 23:97–103

Um-e-Aiman, N Nisar, T Tsuzuki, A Lowe, JT Rossiter, A Javaid, G Powell, R Waseem, SH Al-Mijalli, M Iqbal (2021). Chitin nanofibers trigger membrane bound defence signalling and induce elicitor activity in plants. *Intl J Biol Macromol* 178:253–262

Velmurugan P, SC Hong, A Aravinthan, SH Jang, PI Yi, YC Song, ES Jung, JS Park, S Sivakumar (2017). Comparison of the physical characteristics of green-synthesized and commercial silver nanoparticles: Evaluation of antimicrobial and cytotoxic effects. *Arab J Sci Eng* 42:201–208

Velmurugan P, J Shim, K Kim, BT Oh (2016). *Prunus yedoensis* tree gum mediated synthesis of platinum nanoparticles with antifungal activity against phytopathogens. *Mater Lett* 174:61–65

Velmurugan P, S Sivakumar, S Young-Chae, J Seong-Ho, Y Pyoung-In, S Jeong-Min, H Sung-Chul (2015). Synthesis and characterization comparison of peanut shell extract silver nanoparticles with commercial silver nanoparticles and their antifungal activity. *J Ind Eng Chem* 31:51–54

Wang C, M Zhao, J Li, J Yu, S Sun, S Ge, Y Huang (2017a). Silver nanoparticles/graphene oxide decorated carbon fiber synergistic reinforcement in epoxy-based composites. *Polymer* 131:263–271

Wang J, H Chen (2018). Nanoparticle synthesis methods and their applications. *J Mater Chem B* 6:4200–4215

Wang J, Y Qiufang, S Chengmin, J Chunde, S Qingfeng (2017b). One-step preparation of graphene oxide/cellulose nanofibril hybrid aerogel for adsorptive removal of four kinds of antibiotics. *J Nanomater* 2017:5150613

Wang L, C Hu, L Shao (2017c). The antimicrobial activity of nanoparticles: Present situation and prospects for the future. *Intl J Nanomed* 12:1227–1249

Worrall EA, A Hamid, KT Mody, N Mitter, HR Pappu (2018). Nanotechnology for plant disease management. *Agronomy* 8:285

Yao W, M Qu, X Cui, R Xia, X Liu (2020). Optimization of synthesizing silver nanoparticles from *Trichoderma* strains for inhibition of *Fusarium oxysporum*. *Chin J Biotechnol* 36:1859–1868

Yemmireddy VK, YC Hung (2015). Effect of binder on the physical stability and bactericidal property of titanium dioxide (TiO_2) nanocoatings on food contact surfaces. *Food Cont* 57:82–88

Zabrieski Z, E Morrell, J Hortin, C Dimkpa, J McLean, D Britt, A Anderson (2015). Pesticidal activity of metal oxide nanoparticles on plant pathogenic isolates of *Pythium*. *Ecotoxicology* 24:1305–1314

Zhou Y, ZL Wang (2015). Nanoparticle synthesis. *Chem Soc Rev* 44:2032–2052

Zou L, S Peng, W Liu, X Chen, C Liu (2015). A novel delivery system dextran sulfate coated amphiphilic chitosan derivatives-based nanoliposome: Capacity to improve *in vitro* digestion stability of (-)-epigallocatechin gallate. *Food Res Intl* 69:114–120