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Eco-friendly Management of Phytopathogens through Nanopesticides: A Sustainable Approach

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Abstract

Biopesticides have frequently been the focus of attention on a global scale as a safer alternative to chemical pest control that may provide less damage to both humans and the environment. The usage of biopesticides is rising rapidly worldwide, at 10 per cent a year. With the idea of limited application for most significant impact, nanotechnology has produced novel tools for pest management in agriculture, including nanopesticides and nanosensors. In contrast to conventional chemical pesticides, nanopesticides are formulations of a pesticide's active component in nanoform that have delayed degradation, targeted distribution, and controlled release of the active ingredient over longer periods of time. In accordance with lots of studies, incorporating certain biological agents in nanoparticulate systems increases their effectiveness against pests while lowering losses resulting from physical deterioration. The development and evaluation of nanobiopesticides have been the subject of laboratory-only research to date using techniques like the creation of nanocomposites, nanoengineered biopesticides, coating nanoparticles with bio-pesticides etc. The formulation of appropriate, globally acceptable bio-safety and registration requirements is necessary to enable the effective use of these formulations for pest management at the field level.

Key Words	Bioformulation, Nanopesticides, Phytopathogens, Plant protection, Sustainability
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Introduction

Nanotechnology is revolutionizing agricultural and food waste in underdeveloped countries via sustainable agriculture and circular economy application (Preethi et al. 2024). In developing countries, more than 60% of the population relies upon agriculture for their livelihood either directly or indirectly. In present days, agricultural scientists are facing challenges like climate change, stagnation in crop yields, multi-nutrient deficiencies, low nutrient use efficiency, declining soil organic matter, shrinking arable land and reduced water levels and shortage of labour (Elizabath et al. 2019). To counter these issues many agriculturists and environmentalists have designed many practices for sustainable development and bioformulations are one of them. In all the green practices developed, there were limitations in effectively delivering the crop growth requirements (Sahai et al. 2019). These delivery models called carriers, these carriers can deliver pesticides, fertilizers, biocontrol agents and so many which are required for plants. Nanoparticles are small molecules with a size range of 1–100 nm with different physiochemical properties (El-Saadony et al. 2019). Nano-fertilizers have a high sorption capability, a large surface area and regulated release kinetics to specific sites, making them a better delivery system to provide fertilizers to the plants (Rameshaiah et al. 2015). Addition of fertilizers to soil may lead to loss of fertilizers and therefore more fertilizer should be added to compensate loss (Ombódi and Saigusa 2000), whereas foliar fertilizer application is effective but nutrients might fail to penetrate cell wall pores as their size vary from 5 to 20 micron (Benzon et al. 2015), while nanoparticles with smaller diameter can easily pass through cell wall pores (Moore 2006). The features of nano-fertilizers are delivering the appropriate nutrients for enhancing plant growth through soil and foliar applications, they are cost effective and sustainable sources for plant nutrients, they help in preventing pollution, they have a high fertilization efficiency (Guru et al. 2015).

Irrational use of pesticides possess threat to ecosystem and human health (Kuhlbusch et al. 2018). Nanoencapsulation of pesticide can help in slow and controlled release of pesticide for a prolonged time reducing loss of unwanted pesticide (Agrawal and Rathore 2014). Nanoparticles were also used against viruses and in managing maturation of fruits (Hawthorne et al. 2014). Nanotechnology is used in agriculture and food production as nano sensors for monitoring crop growth and pest control by early detection of disease-causing pests in plants (Bhagat et al. 2015). Remarkable opportunities were introduced in agriculture by using nanotechnology-based delivery systems, resulting in smart controlled slow release of fertilizers and agrochemicals required to enhance crop yield (Prasad et al. 2017). Agrochemical industries are mainly focusing on increasing crop yields regardless the risk of nano technology, while toxic effects of nanotechnology towards environment and human health received little to no attention. Therefore, it is necessary to also focus on nanoparticles reactivity, biodegradation time, levels of bioaccumulation, retention time, toxicity of waste (Chaud et al. 2021).

The integration of nanotechnology and agriculture has emerged as a ray of hope in a time when concerns about global sustainability are on the rise. This progressive approach might address some of the most urgent issues confronting the globe today, like the sustainable handling of food and agricultural waste, and encourage the adoption of circular economy principles, especially in poor nations. A substantial and frequently underutilized resource that is essential to the sustainability of the food supply chain is agricultural and food waste (Manna et al., 2023). Taking into account research findings worldwide, we found significant improvements with nanotechnology over traditional methods which underscores the practical benefits of nanotechnology, including increased crop yields, efficient resource use, and reduced environmental footprint. This comprehensive review aims to investigate the association between agricultural systems and nanotechnology, emphasizing how it might improve resilience, sustainability, and production.

Nanotechnology in Agriculture

Nanoscience is being investigated in the areas of water management, controlled applications of agrochemicals, plant hormone administration, seed germination, transfer of genes of interest and nano-biosensors (Hayles et al. 2017). Additionally, by conjugation, adsorption, or encapsulation, nanoparticles are created to have the appropriate features (size, shape, surface area, etc.) for use as a protectant, therapeutant or for the site-specific delivery of active substances like fungicides (Khandelwal et al. 2016). Plants can be treated with nano-based materials through foliar spraying, soil application, seed treatment, and root dip treatment. In plants, the metallic oxides, nonmetals, metalloids, polymeric and carbon nanomaterials show growth-promoting and disease-suppressive properties (Elmer et al. 2018). The most often studied nanoparticles are made of iron, zinc oxide, silver, gold and many more. The use of nanoparticles involves three primary mechanisms such as (a) using nanoparticles as biosensors (b) using nanoparticles as therapeutics or protectants and (c) using nanoparticles as intelligent delivery systems for active ingredients like target genes or fungicides. Against a range of soil-borne pathogens, such as *Fusarium oxysporum, Sclerotium rolfsii, Rhizoctonia solani* and *Sclerotinia sclerotiorum* (Abdelrhim et al. 2021), *Ralstonia solanacearum* (Khairy et al. 2022), soil-borne viruses, such as Barley yellow mosaic virus (BaYMV) (Aref et al. 2012) etc., the nanoparticles may act as protective or therapeutic agents. The primary methods of combating microbes are agglutination and rupture of cell membranes, suppression of RNA, protein, toxin, and enzyme synthesis, including H^+ATPase, as well as obstruction of nutrition flow (Dakal et al. 2016). Additionally, nanoparticles serve as carrier molecules, enabling the targeted release of active substances into the plant system and lowering the amount of chemicals released into the environment. Improved pesticide water solubility, site-specific distribution and uptake by target sites, longer shelf life, less impact on non-target organisms and residual environmental effects are just a few advantages of the nano-based formulations (Hayles et al. 2017). Furthermore, nano-based formulations exhibit higher stability and activity in comparison to conventional pesticides, especially in adverse environmental circumstances like rainfall and UV exposure. Multifunctional role of nanotechnology showed in Fig. 1.

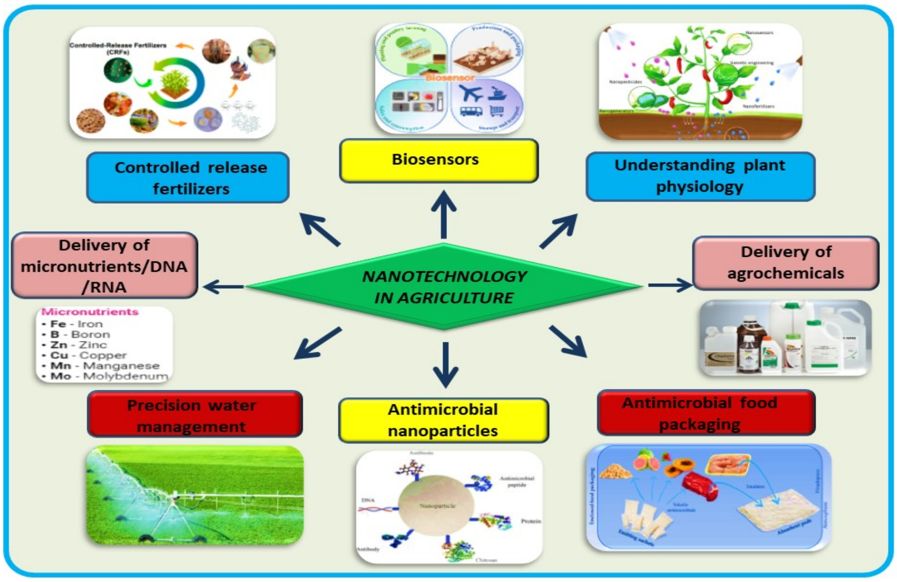

Fig.1 ~~Versatile role of Nanotechnology in Agriculture~~ (Source: made by authors)

The Multifaceted Role of Nanotechnology in Sustainable Crop Production and Disease Management

Another important aspect of plant health management is the use of fertilizers. Nanofertilizers bear the potential to increase the release and uptake efficacy of nutrients thereby boosting plant disease resistance. It has widely been explored in plant/disease systems *viz*., Fusarium wilt in tomato, chrysanthemum, root and crown rot in asparagus, red root rot in tea, Verticillium wilt in brinjal (Elmer et al. 2018).

Nanoparticles

Nanoparticles are characterized as particles in which at least half have dimensions ranging from 1 to 100 nm. Compared to bulk materials, nanoparticles have a substantially greater surface-to-mass ratio (Modena et al. 2019). Various types of nanoparticles tabulated in Table 1. Nanoparticle characteristics, such as their optical, magnetic and electrical qualities, differ greatly from those of traditional materials (Khan et al. 2017). Nanoparticles can be found in diverse chemical compositions, spanning from micelles to metal (oxide), synthetic polymers to large biomolecules. Each of these materials exhibits distinct chemistry, analysable through various methods such as optical spectroscopy, X-ray fluorescence and absorbance, Raman spectroscopy, and solid-state NMR (Ma 2016). While they are commonly assumed to be spherical, nanoparticles actually exhibit a wide range of geometric and irregular shapes (Li et al. 2014).

Table 1. Different types of Nano materials and their applications

S.N.	Types of nano particles	Examples	Applications
1.	Metal based nanoparticles	Copper, silver, silicon, Titanium oxide, zinc	Zinc based nanoparticles inhibit fungal growth Copper nanoparticles may act asbio-pesticides and silicon- germanium isused as soil supplementation.
2.	Nanoscale polymers	Nylon-6/montmorillonite montmorillonite-Alginate	Mainly used as in catalytic processes and moisture removal
3.	Carbon based nano materials	Carbon nanotubes [CNT], fullerenes	Improving plant health and environmental cleanup
4.	Nano emulsions	Beta-cypermethrin methyl laurate, alkyl polyglycolides	Nano emulsions are finding application in diverse areas such as drug delivery, food, cosmetics, pharmaceuticals, and material synthesis
5.	Clay encapsulations	Organic layered double hydroxides, anionic inorganic	clay tubes are an excellent miniature container for encasing chemical agentsand attractive for applications in drug delivery, antimicrobial materials, self- healing polymeric composites and regenerative medicine

6.	Nanogels	Polyethyleneimine PEG -polyplex nanogel	(N-isopropylacrylamide) (PNIPAM)-based nanogels with high deformability structure were successfully constructed for smart pesticide delivery and effective pest Control
7.	Dendromers (Nanoparticles)	poly(L-lysine) (PLL), and triazene	potential applications of dendrimers include gene transfection, a catalyst for nanostructures, rheology modification

Nanoparticles can be characterized using high-resolution microscopy technologies, such as electron and scanning probe microscopy, capable of detecting features with sub-manometer resolution (Park et al. 2015). The potential to synthesize nanoparticles with porous frameworks has significantly broadened the application scope of nanomaterials (Baeza et al. 2017). The surface-to-volume ratio of the nanoparticles is dramatically increased by porosity, exceeding that of solid particles with identical diameters by many orders of magnitude (Modena et al. 2019). Various types of nanoparticles exist, including zerovalent metal nanoparticles, metal oxide nanoparticles, carbon nanotubes, nanocomposites, quantum dots among others. Each of these holds distinct significance in the realm of nanotechnology (Singh et al. 2019). Various techniques are employed for synthesizing nanoparticles, including biological, chemical, and physical methods. However, chemical and physical approaches are not cost-effective and often involve the use of hazardous and toxic compounds. It is widely acknowledged that these methods pose risks to human and environmental health due to harmful radiation, synthetic reductants in concentrated forms, and stabilizing agents. In contrast, biological methods relying on plants and microbes are more efficient, cost-effective, and environmentally friendly. They entail a one-step bio reduction process, offering a safer alternative with fewer adverse impacts (Ul Haq and Ijaz et al. 2019).

History and Timeline

In response to the growing difficulties associated with sustainable production and ensuring food security, substantial technological progress and creative innovations have emerged in the agricultural sector in recent years (Dwivedi et al. 2016; Kou et al. 2018; Xiao et al. 2013). Nanotechnology is one such technological advancement which stands out as one of the most promising advancements in the 21st century. The concept of nanotechnology was first time introduced by an American physicist and Nobel Prize recipient, Richard Feynman in 1959. He delivered a lecture titled "There's Plenty of Room at the Bottom" at the annual meeting of the American Physical Society, which took place at the California Institute of Technology (Caltech) (Bayda et al. 2019). The term 'nanotechnology' was first time used and defined by the Japanese scientist Norio Taniguchi, who served as a professor at the Tokyo University of Science, in 1974 (Khan and Rizvi 2014). According to him, "nanotechnology primarily involves the manipulation, assembly, and alteration of materials at the scale of individual atoms or molecules" (Taniguchi et al. 1974). After Feynman's discovery of this new field of research, it piqued the interest of many scientists. Invention of scanning tunnelling microscope in 1981 and discovery of fullerene/carbon "buckyballs" (C60) in 1985 leads to emergence of nanotechnology (Kroto et al. 1985). In 1986, K. Eric Drexler published the first book on nanotechnology, titled "Engines of Creation: The Coming Era of Nanotechnology." This publication contributed to the increasing popularity of the concept of "molecular engineering" (Drexler 1986). Later on, in 1991, Drexler, Peterson, and Pergamit released another book titled "Unbounding the Future: The Nanotechnology Revolution." In this book, they introduced the terms "nanobots" and "assemblers" to describe nano processes in the field of medicine. It was after this publication that the well-known term "nanomedicine" was first coined and used (Drexler et al. 1991).

Synthesis of Nano-bioformulations

Biological Synthesis of Nanoparticles by Microorganisms

Since the beginning of life on earth, biological beings and inorganic materials have been in constant contact with one another. With a well-organized mineral deposit, life may exist on this planet because of this regular contact. The relationship between inorganic molecules and living species has attracted the curiosity of scientists more and more recently. Numerous bacteria can create inorganic nanoparticles through extracellular or intracellular pathways, according to investigations. The synthesis of different nanoparticles using biological methods is covered in this section. The mechanism involved in synthesis of microbial nanoparticles showed in Fig. 2. The categories of nanoparticles covered are metallic (such as gold, silver and other metal nanoparticles), oxide (which includes both magnetic and nonmagnetic oxide nanoparticles), sulphide and other miscellaneous.

Gold Nanoparticles

The use of gold nanoparticles or AuNPs for elegant glass staining dates back to the Roman era and their history in chemistry is extensive. AuNPs have been utilized for ages to treat a variety of diseases. Michael Faraday, who may have been the first to notice that the properties of colloidal gold solutions differ from those of bulk gold is credited with starting the present age of AuNP synthesis more than 150 years ago (Hayat 1989).

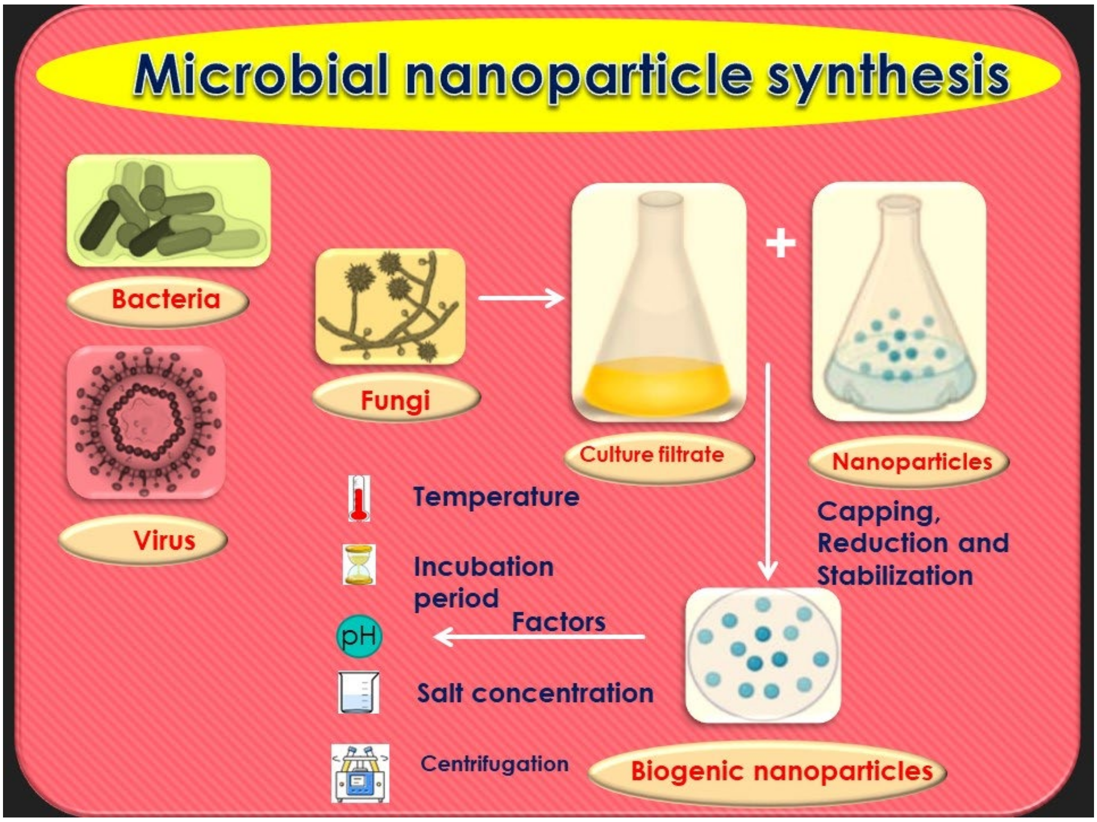

Fig. 2. Depicting various steps involved in synthesis of microbial nanoparticles (Source: made by authors)

The growing need to develop environmentally benign technologies in materials synthesis has brought biosynthesis of nanoparticles—the nexus of nanotechnology and biotechnology—to significant attention (Subbarayudu and Kubendiran 2024). The extracellular production of gold nanoparticles by the actinomycete *Thermomonospora* sp. and the fungus *Fusarium oxysporum* has been reported by Ahmad et al. (2003). Additionally, they found that the fungus *Verticillium* sp. was able to synthesise gold nanoparticles inside of cells (Mukherjee et al. 2001). Bacterial cells can easily precipitate gold particles with nanoscale dimensions when they are incubated with Au^{3+} ions (Southam and Beveridge 1996).

Silver Nanoparticles

Similar to its bulk counterpart, silver nanoparticles have potent antibacterial activity against both Gram-positive and Gram-negative bacteria including strains of the latter that are extremely multi-resistant, like methicillin-resistant *Staphylococcus aureus* (Panáček et al. 2006). The creation of biomimetic methods for the formation of sophisticated nanomaterials is a result of the secrets found in nature (Gareev et al. 2022). Scientists have recently been working to employ microbes as potentially environmentally benign nanofactories for the manufacture of silver nanoparticles. It is known that a variety of bacteria can decrease the Ag^{+} ions to produce silver nanoparticles, the majority of which are spherical in shape (Fayaz et al. 2010). The bacterium *Pseudomonas stutzeri* AG259, isolated from a silver mine was shown by Klaus and colleagues to play a significant role in the reduction of Ag+ ions and the development of distinct sized and topographically defined AgNPs within the periplasmic space of the bacteria when it was placed in a concentrated aqueous solution of silver nitrate (Klaus et al. 1999). When fungus, *Verticillium, Fusarium oxysporum* or *Aspergillus flavus* were used, AgNPs were created as a film in solution or deposited on the cell's surface (Jain et al. 2011).

Oxide Nanoparticles

Over the past ten years, there has been a sharp increase in the industrial use of metallic oxide nanoparticles in a wide range of applications. These applications involve the utilisation of metallic oxide nanoparticles such as silicon, titanium, iron and others, increasing the sensitivity of humans and other animals to these nanoparticles through occupational and environmental exposure (Lai et al. 2007). However, because regulatory oversight has not focused on the environmental impact of metallic oxide nanoparticles, the health implications of exposure to these particles in humans and other species have not been thoroughly studied (Lai et al. 2007). One significant class of microbial nanoparticles produced by microorganisms is the oxide nanoparticle. The process of biogenesis of oxide nanoparticles in this section. The majority of the biological systems and magnetotactic bacteria utilized to produce magnetic oxide nanoparticles and nonmagnetic oxide nanoparticles (Li et al. 2011).

Copper Oxide (CuO) Nanoparticles

Copper has been shown in multiple investigations conducted over the past two years to have exceptional antibacterial activity at the nanoscale (Cuevas et al. 2015). Copper as a metal or copper oxides exhibit broad-spectrum biocidal activity. Since copper is a necessary metal for all living things, it may find use in biomedical applications unlike silver nanoparticles which have been the subject of substantial research for their antibacterial properties (Rubilar et al. 2013). It's vital to remember that copper is currently around ten times less expensive on the market than silver so a process that makes use of copper would end up being quite economical. However, it has been noted that compared to silver nanoparticles, copper nanoparticles are less hazardous (Bondarenko et al. 2013). Under ambient conditions, microorganisms like *Fusarium oxysporum* can extract copper from integrated circuits found on electronic boards (Cuevas et al. 2015). No significant polydispersity was found in the pH range of 5–9 in the investigation of the biogenic synthesis of copper oxides from CuSO4 by *Penicillium aurantiogriseum, P. citrinum, P. waksmanii*, and *F. oxysporum* (Honary 2012; Hosseini et al. 2012). Only a few numbers of research evaluating various fungal strains for copper nanoparticle production have been published. It has been observed that certain strains of *F. oxysporum* and *Penicillium* sp. are capable of biosynthesizing Cu_2S and copper oxide nanoparticles (Honary et al. 2012; Hosseini et al. 2012). In the presence of three different copper salts. Ability to synthesise copper and copper oxide nanoparticles using a mycelium-free extract made by the white-rot fungus *Stereum hirsutum* (Cuevas et al. 2015). They also assessed the ability to characterise and evaluate the role of proteins in the formation of the nanoparticles.

Bioformulations

Bioformulation is a green practice developed by environmentalists and agriculturists to address issues related to biomagnification and chemical toxicity in the environment (Sahai et al. 2019). Any biologically active chemicals generated from microbial biomass or products containing microorganisms and their metabolites that might be utilized to promote plant development, acquire nutrients, and manage disease in an environmentally acceptable way are referred to as bioformulations. Essentially, a bioformulation is a blend of an active ingredient within a formulated product composed of inert (inactive) substances (Aamir et al. 2020). Bioformulation is a ready-to-use formulation that contains living cells or their metabolites (of one or more strains), supported by nontoxic and inert compounds called carriers to sustain the viability and efficiency of cells or metabolites and to lengthen their shelf life (Usta 2013). For promoting plant development, controlling phytopathogens, preserving soil fertility, and preventing disease, bio formulated solutions provide environmentally friendly substitutes to commonly used chemical fertilizers and pesticides (Arora and Mishra 2016; Khatri and Bhateria 2023). A bioformulation is a preparation of microorganisms or their active gradient that can be used in place of chemical fertilizers/pesticides. However, for the formulation to be successful, a true bio-formulated product needs to have an active component and be made of living microbes, spores, or their derivatives. Talc, Peat, carboxymethylcellulose, vermiculite, and polymers, particularly xanthan gum and diatomaceous earth are some of the most popular inert active materials. The antagonistic microbial cells have been discovered to be more effectively incorporated into the plant system and rhizosphere by using inert carrier-based bioformulations, which could be applied both foliarly and topically (Aamir et al. 2020). Starch, methyl cellulose, silica gel and gum are a few additives that help bioformulated products withstand the extreme weather conditions while also enhancing their physical, chemical, and nutritional qualities (Schisler et al. 2004). Some of the microorganism that are used in bioformulation are the strains of *Trichoderma* spp*., Rhizobium, Bacillus, Glomus, Lactobacillus, Azospirillum, Burkholderia, Rhodococcus, Pseudomonas fluorescens, Bacillus subtilis, Azotobacter, Pseudomonas* spp., *Actinobacteria, Bradyrhizobium, Acetobacter, Paenibacillus, Serratia, Herbaspirillum,* Blue green algae*, Paenibacillus elgii, Pseudomonas putida,* mycorrhizal fungi etc (Bidyarani et al. 2022).

Various nano-bioformulations

Nano-bioformulation as a nano-biofertilizer

Nano-biofertilizer refers to a product comprising nano-scale materials paired with a particular microbial inoculant. Its nanoscale properties influence its application method, allowing for precise and timely nutrient delivery to field crops. Simultaneously, it enhances the functional advantages of the bio-fertilizer component within the formulation. Bio-fertilizers encompass crucial root-associated microorganisms, such as fungal mycorrhizae, *Azospirillum*, blue-green algae (BGA) and *Bacillus* species (Shanware and Taiwade 2022). The utilization of nano-biofertilizers has reduced the indiscriminate use of agrochemicals and contributed to substantiating integrated nutrient management practices for the consistent productivity of crops (Mir et al. 2015). The surface area of nutrients is increased through the process of making nano-biofertilizers, which involves coating the surface of bio-fertilizers with nanoparticles. This improves both their stability and the efficiency with which soil nutrients are taken up (Mala et al. 2017). This approach entails the live formulation of microorganisms that stimulate bacterial activity for improved plant growth. This formulation is then coated with a nanoscale polymer, a method commonly known as nanoencapsulation (Shebl et al. 2019). One of the notable advantages of nanoencapsulation technology lies in its flexibility, particularly in protecting the components of bio-fertilizers containing PGPR (plant growth-promoting rhizobacteria). This innovation has resulted in an extended shelf life and has also enabled precise control over the release of PGPR mechanisms (Gouda et al. 2018). Silicon, zinc, copper, iron, and silver are among the most frequently employed nanoparticles in the formulation of nanobiofertilizers (Akhtar et al. 2022). Three crucial steps are involved in the creation of nanobiofertilizers: (1) the growth of the biofertilizer culture; (2) its encapsulation with nanoparticles; and (3) the assessment of its efficacy, quality, purity and shelf life (Panichikkal et al. 2021). Various formulations have been developed to improve crop production, such as the combination of nano-Zn and biofertilizer, which has been shown to enhance the physiochemical properties of sugarbeet plants. Additionally, the application of a combination of nanopharmax and humic acid in black cumin may boost the nutritional content of cumin (Shanware and Taiwade 2022). The application of Nano-biofertilizer containing specific bio-inoculants, such as *Azotobacter* strain, *Pseudomonas putida*, and *Pantoea agglomerans* strain P5, has been studied. This application has been found to raise nutrient concentrations and increase pigment content. Moreover, it enhances various plant parameters including photosynthetic productivity, leaf area, sucrose content, and other factors on different parts of the plants.

Nanobioformulation as a nanobiopesticide

Despite their pesticidal effectiveness, biopesticides have some drawbacks. Innovative formulations have been created to increase their efficacy and fix current problems (Ayilara et al. 2023). This includes nanoformulations with a smaller amount of the active ingredient that are appropriate for diverse crop protection applications**.** Management of plant pathogens by use of various nanoparticles depicted in Fig. 3.

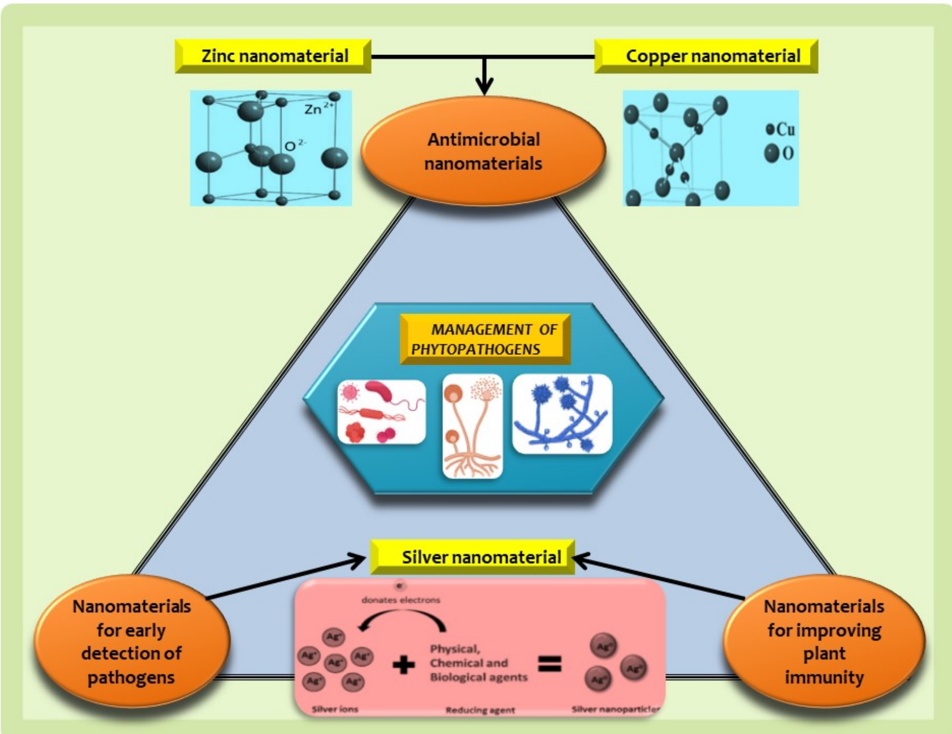

Fig. 3 Management of plant pathogens by use of various nanoparticles (Source: made by authors)

The resulting biopesticidal nanoformulations can be used directly as pesticides when nanomaterials are stabilized with biopesticides and nanobiopesticides are incorporated. By gaining efficiency at lower dosages of active components, these nanobiopesticides aid in successful pest management (Vimala Devi et al. 2019).

Examples of various nano bioformulations as nanobiopesticides

Silver nanoparticles were developed and capped with the leaf extract of *Aristolochia indica* (Siva and Santhosh Kumar 2015). Management of various plant diseases by using different nanoparticles tabulated in Table 2. The resulting nanoparticles exhibited toxicity against the larva of *Helicoverpa armigera*. In field conditions within a cotton crop, it was observed that the combination of silver nanoparticles with the pyrethroid compound bifenthrin, extracted from *Chrysanthemum*, demonstrated greater toxicity to *Lygus hesperus* compared to *Acheta domesticus*. Essential oils were extracted from *Zanthoxylum rhoifolium* leaves (Christofoli et al. 2015). Subsequently, nanospheres were developed with these oils using nanoprecipitation, resulting in a notably high encapsulation efficiency of 96 per cent. The effectiveness against adult *Tribolium castaneum* (Herbst) was examined by utilizing polyethylene glycol nanoparticles as carriers for garlic essential oil. The eco-friendly production of silver nanoparticles and lead nanoparticles, utilizing extracts from *Euphorbia prostrate* and *Avicennia marina* (a mangrove plant), demonstrated pesticidal activity against *Sitophilus oryzae*. The outcomes revealed a 100% mortality rate after a 4-day treatment period (Vimala et al. 2019). Coating derived from cashew gum was applied to an insecticide extract obtained from Moringa seeds. This coating led to a notable enhancement in entrapment efficiency, rising from 39% to 60%. Remarkably, the released insecticide remained effective for up to 55 days following application (Paula et al. 2012). Chitosan nanoparticles (ChNPs) loaded with silver metal ions exhibit heightened antibacterial efficacy, demonstrating a low minimum inhibiting concentration (MIC) of 3 μg/ml against *Escherichia coli* and 6 μg/ml against *Staphylococcus aureus* (Du et al. 2008). Titanium dioxide nanoparticles (TDNPs), synthesized through *T. viride*, were evaluated for their bioefficacy against larvae and pupae of *Helicoverpa armigera*. The TDNPs exhibited remarkable effectiveness, causing 100 per cent mortality in first, second and third instar larvae of *H. armigera* at a concentration of 100 ppm (Kamaraj et al. 2018). Extracellular synthesis of silver nanoparticles (AgNPs) utilizing the bacterium *Serratia* sp. BHU-S4 revealed an inhibitory impact on the fungus *Bipolaris sorokiniana.* The AgNPs produced through biogenic means displayed complete inhibition of conidial germination, both on the growth medium and on wheat leaves artificially inoculated with fungal conidia (Mishra et al. 2014). Nanoemulsions formulated with neem and citronella essential oils demonstrated potent antifungal activity against *Rhizoctonia solani* and *Sclerotium rolfsii* (Ali et al. 2017). *Conyza dioscoridis*, *Melia azedarach*, and *Moringa oleifera* extracts were used to make silver nanoparticles (Ag-NPs), which showed increased nematocidal action against eggs and young of the root-knot nematode *M. incognita* (Abbassy et al. 2017). The prospective use of mycogenic zinc oxide nanoparticles (ZnONPs) as a preventative measure against potato late blight looks promising (Singh et al. 2022). Silver and gold nanoparticles were biosynthesized using *Trichoderma atroviride*, demonstrating potential for biological control of *Phomopsis* canker disease in tea plants. The nanoparticles exhibited antagonistic activity against the pathogen (Ponmurugan 2017).

***Bacillus* based nanobiopesticide for disease and pest reduction**

Due to its great entomopathogenic potential, the genus *Bacillus* is frequently used as a biocontrol agent for managing both diseases and insects (Mampallil et al. 2017). The *Bacillus* group of bacteria is found in a diverse range of environments and is renowned for its ability to produce numerous antimicrobial compounds with diverse structures. Approximately 5–8% of its genome is dedicated to the synthesis of secondary metabolites (Fira et al. 2018). The creation of a nano-formulation using Bt relies on top-down methods of micronization, including ball and jet milling, as well as high-pressure homogenization. These processes are employed to convert coarse powder into fine particles within the size range of 2–5 µm (Vimala Devi et al. 2019). A nanobioformulation, functioning as a nanobiopesticide is a composite of nanoparticles and microbial biocontrol agents (such as *Bacillus* sp.) (Padmakumar et al. 2023). This combination capitalizes on the higher surface area/volume ratio of nanoparticles, leading to enhanced effectiveness, reduced toxicity, increased solubility, durability and versatility. Various types of nanoparticles, including Ag, Al, Au, MnO, ZnO etc., can be integrated with different *Bacillus* species like *B. thuringiensis*, *B. subtilis*, *B. licheniformis*, etc. This integration aims to create an effective, efficient and environmentally friendly nanobiopesticide capable of suppressing the growth of diseases and pests (Kumar et al. 2021). Strains of *B. subtilis* have been identified for their ability to inhibit the growth of various plant pathogens, including *Phomopsis*, *Colletotrichum truncatum*, *Rhizoctonia solani*, *Macrophomina phaseolina*, *Sclerotinia sclerotiorum*, *Colletotrichum gloeosporioides*, *Phytophthora infestans* and others (Widnyana and Javandira 2016).

Table 2. Management of soil borne plant pathogenic organisms by using various Nanoparticles

Nanomaterial	Type of pathogen	Target pathogen	Crop	Effect	Reference
AgNPs	Fungi	*Macrophomina phseolina, Fusarium fujikuroi and Rhizoctonia solani*	Cotton (*Gossypium herbaceum)*	Reduction in mycelial growth and disease of cotton seedlings	(Zaki et al 2022)
MgONPs	Fungi	*Phytophthora infestans*	*Potato (Solanum tuberosum)*	Inhibition of *Phytophthora infestans* by cell membrane distortion, oxidative stress, disruption of metabolic pathways and membrane transport activity with no harmful effect on potato	(Wang et al. 2022)
Copper oxide nanoparticles (CuONPs)	Fungi	*Phytophthora nicotianae*	Tobacco (*Nicotiana tabacum*)	33.69% increase in control efficacy and tobacco black shank disease suppression without inducing phytotoxicity at 100 mg L−1 of CuO NPs treatment	(Juan et al. 2022)

Capped AgNPs	Fungi	*Sclerotinia sclerotiorum*	Vegetables	Inhibition of mycelial growth and sclerotia germination	(Guilger et al. 2021)
Chitosan NPs	Fungi	*Fusarium oxysporum, Rhizoctonia solani, Sclerotium rolfsii*	Cereals, Vegetables	Reduction in mycelial growth	(Boruah and Dutta 2021)
Carboxymethyl cellulose coated core/shell SiO2@Cu nanoparticles	Fungi	*Phytophthora capsici* Host: *Black pepper*	Black pepper (*Piper nigrum*)	Antifungal activity against *P. capsici* with MIC 75 ppm	(Hai et al. 2021)
Zinc oxide (ZnO), Iron oxide (FeO) and Copper oxide (CuO) nanoparticles	Bacteria	*Ralstonia solanacearum* Host*: Tomato*	Tomato (*Solanum lycopersicum*)	Reduced incidence of tomato bacterial wilt disease	(Jiang et al. 2021)
AgNPs	Fungi	*Sclerotinia sclerotiorum*	Mustard (*Brassica juncea*)	Inhibition of hyphal growth, sclerotial formation and myceliogenic germination of sclerotia	(Tomah et al. 2020)
Magnesium oxide nanoparticles (MgONPs)	Fungi	*Phytophthora nicotianae and Thielaviopsis basicola*	Tobacco (*Nicotiana tabacum*)	Inhibition of fungal growth, spore germination and impediment of sporangium development	(Chen et al. 2020)
AgNPs	Nematodes	*Meloidogyne javanica*	Tomato (*Solanum lycopersicum*)	Nematicidal activity on egg hatchability and juvenile mortality. Reduction in number of galls, egg masses, number of females per root/plant and mortality of juveniles.	(Ghareeb et al. 2020)
Silver Nanoparticles (AgNPs)	Fungi	*Sclerotium rolfsii, Rhizoctonia solani, Sclerotinia sclerotiorum* and *Fusarium oxysporum*	Cereals, Pulses and vegetables	Mycelial growth inhibition at 100 ppm AgNP	(Kaman and Dutta 2019)
Copper/Iron NPs	Nematodes	*Meloidogyne incognita* and *M. javanica*	Tomato (*Solanum lycopersicum*)	Nematicidal activity such as paralysis, biological cycle arrest, reduction in number of galls with lowest EC50 value as	(Gkanatsiou et al. 2019)

				compared to commercial nematicides	
AgNPs	Fungi	*Fusarium solani* and *Macrophomina phaseolina*	Strawberry (*Fragaria ananassa*)	The nanoparticle showed broad spectrum antagonism against *M phaseolina* (67.05%) and *F. solani* (83.05%)	(Ruiz-Romero et al. 2018)
Gold nanoparticles (AuNPs)	Virus	*Barley yellow dwarf virus (BaYDV)*	Barley (*Hordeum vulgare*)	A high yield of ruined virus like particles (VLPs) were also observed	(Alkubaisi and Arif 2017)
AgNPs	Fungi	*Phomopsis* sp. Host*:* Soybean seeds	Soybean (*Glycine max*)	Absolute inhibition of the pathogen was observed 270 and 540 ppm concentration	(Mendes et al. 2014)

Mode of action of nanobioformulation:

When beneficial bacteria are introduced into the soil as biofertilizers, they colonize and multiply quickly. This microbial activity plays a crucial role in converting typically insoluble and organic nutrients into soluble forms, making it easier for plants to absorb them. Biofertilizers that include nitrogen-fixing bacteria like *Rhizobium, Frankia, Xanthomonas*, and others have the capability to produce the nitrogenase enzyme.

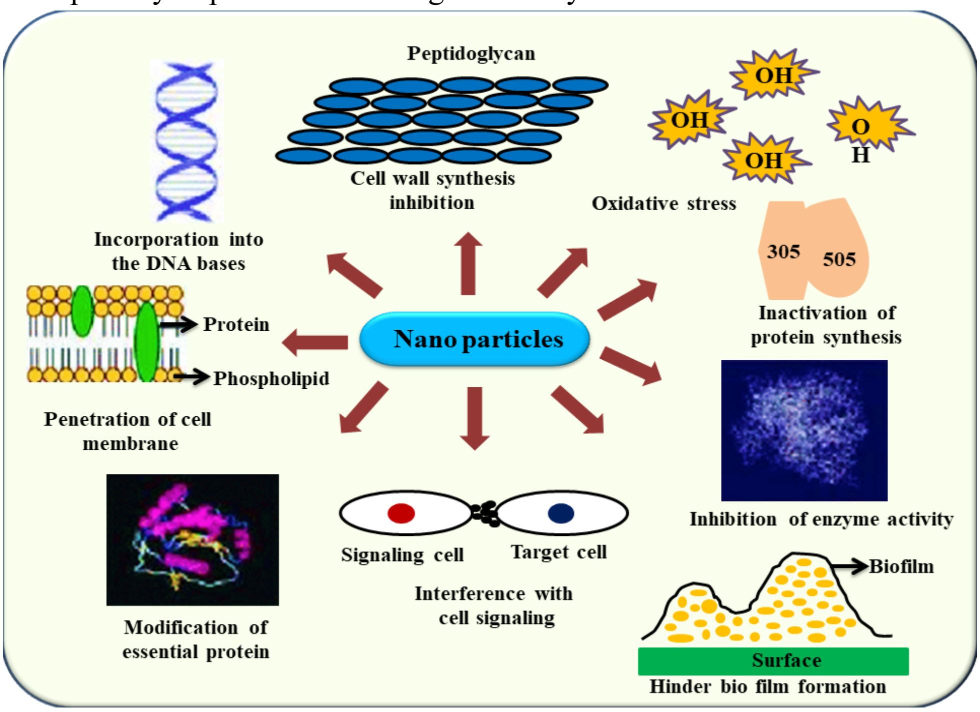

Fig.4. ~~Illustrating various mode of action of bionanoformulation~~

(Source: made by authors)

Unveiling the Mechanisms: Diverse Modes of Action of Bionanoformulations in Enhancing Agricultural Productivity and Disease Control

This enzyme, in turn, facilitates the conversion of nitrogen into ammonia (Patel et al. 2023). Phosphate-solubilizing microorganisms like *Bacillus, Aspergillus*, and *Pseudomonas* produce enzymes or organic acids that play a catalytic role in converting insoluble phosphate complexes, such as aluminum and tricalcium phosphates, into soluble forms that plants can readily absorb (Tian et al. 2021). These microorganisms, known as Plant Growth-Promoting Rhizobacteria (PGPR), also release substances like iron, vitamins, and hormones that are essential for plant growth. Additionally, the relationship between PGPR and plants is strengthened through cellular communication methods, such as quorum sensing. This serves as a signalling mechanism through which microorganisms assess their environment and coordinate their activities within the rhizosphere (Sarbani and Yahaya 2022).

Advantages and disadvantages of nanobioformulations

Advantages:

Nanobioformulations is the combination of biofertilizers with nanonutrient particles. These nanobioformulations may incorporate one or more beneficial microorganisms that enhance soil productivity, including nitrogen-fixing bacteria, phosphate-solubilizing/mobilizing organisms, and plant growth-promoting stimulators (Tarafdar 2022). Compared to traditional pesticides, nanopesticides offer superior performance and are better suited for widespread use in the global context of climate change and resource scarcity (Wang et al. 2022). Nanoformulations stand out as a vital component in contemporary agricultural technology (Sahu et al. 2021). Nanoformulations encompass the process of coating, encapsulating, adsorbing, or entrapping fertilizers, pesticides, and nutrient supplements within the voids, pockets, or pores of nanomaterials (Bhardwaj et al. 2022). There are various advantages of using nanobioformulation instead of conventional chemical fertilizer. The inoculation of plants with NBFs improves plant development and resistance to stress, utilizing nanobiofertilizer formulations can contribute to the advancement of sustainable agriculture development (Garg et al. 2023). The application of nanobioformulations in agriculture presents an opportunity to enhance global food production sustainability. The significant advantages of nanofertilizers over traditional chemical fertilizers revolve around their nutrient delivery systems (Yadav et al. 2023). For instance, nanofertilizers can release nutrients gradually over a period of 45 to 50 days, in contrast to the 5 to 10 days typical of conventional fertilizers. This extended release improves nutrient use efficiency up to 20 times, reducing nutrient requirements and cutting down on transportation and application costs. Nanoparticles are considered effective carriers for delivering nutrients to specific locations through methods such as encapsulation or creating nanoscale emulsions. Interestingly, the surface coating of nanomaterials on fertilizer particles offers better adhesion due to their higher surface tension compared to conventional surfaces. This improved adhesion facilitates controlled nutrient release (Brady and Weil 1999; DeRosa et al. 2010; Bhattacharyya et al. 2016). Nanobioformulations possess a great advantage over conventional fertilizers as they exhibit specificity, reduced toxicity, and gradual release of nutrients (Cui et al. 2010). Another advantage of using nano biofertilizers is it prevents soil from becoming excessively loaded with salts, a common issue associated with the over-application of conventional fertilizers (Tarafdar 2022). Moreover, the application of nanotechnology in agriculture counteracts the problems such as crop yield, food security, climate change, and sustainability (Mishra et al., 2014).

Disadvantages:

Although the future of nanopesticides in agriculture development appears promising, the human exposure to dangerous agrochemicals able to cross biological barriers (e.g., blood-brain barrier, blood-placental barrier, and blood-retinal barrier) is a significant concern as it can cause irreversible damage to vital organs. The risks posed by the exposure to hazardous nanopesticides, which are able to induce toxic and genotoxic events, are currently receiving great attention by studying the effect not only on the chemical composition of the bulk material but also on the physicochemical properties of nanopesticides such as size, electrical charge, and surface properties (Grillo et al. 2012; Zielinska et al. 2020).

According to studies, nanoparticles may have negative impact on soil, plant and animal's health. Nanoparticles have the potential to alter the composition and structure of soil, potentially leading to reduced water retention and nutrient accessibility. Moreover, there is a possibility that plants may absorb these nanoparticles, which could impact food chains and affect plant growth (Ahmed et al. 2021). Nanomaterials may enter in aquatic habitat, potentially affects aquatic ecosystems and may become part of the aquatic food chain. Nanoparticles can easily enter into the biological systems which is not possible for the larger particles. The ability of nanoparticles to cross cell membranes depends on their size. In situations where farm workers are spraying nanoparticles, there is a potential risk of inhalation, which could allow these nanoparticles to enter the bloodstream and potentially reach various target sites within the body, including the brain, liver, or heart (Suppan 2017). These nanoparticles might affect the regulatory mechanisms of enzymes and other proteins (Saptarshi et al. 2013). There is a possibility of nanoparticles entering food chains, with potential implications for human health. Therefore, it is crucial to prioritize the development of a skilled workforce that comprehends the intricacies of agricultural production systems, enabling the successful integration of nanotechnology applications in agriculture (Siddhartha 2014). However, the exact consequences of their presence on human health and aquatic ecosystems remain uncertain at this time (Li et al. 2014). It may adversely affect biodiversity and ecosystem health as even small changes may upset sensitive balances, there are worries about how long-term usage of nano-materials will affect biodiversity and ecosystem dynamics (Ahmed et al. 2021).

Nanopesticides, which are nano-formulated pesticides, offer innovative solutions to pest and disease management. Their effectiveness, however, depends on formulation, target pests, and environmental interactions. Below are the pros and cons of different nano-pesticides with references to specific case studies:

Type of Nano-pesticide	Pros	Cons	References
Nano-Encapsulation	➢ Controlled release reduces application frequency and enhances efficacy.	➢ High cost of nano - carrier synthesis.	Arratia-Quijada et al. 2024; Dinh et al. 2024

	➢ Enhanced targeting minimizes non-target exposure. ➢ Protects active ingredients from degradation.	➢ Potential residue persistence of encapsulation materials. ➢ Limited biodegradability.	
Case Study:	Nano-encapsulated carbendazim effectively controlled *Fusarium oxysporum* with 50% lower doses. Phytotoxicity evaluation of nanoformulated fungicide confirmed that the nanoformulated carbendazim is safer for germination and root growth of the seeds of *Cucumis sativa, Zea mays,* and *Lycopersicum esculantum*.		Sandhya 2024
Nano-Emulsions	➢ Improved solubility of hydrophobic pesticides, enhancing efficacy. ➢ Uniform distribution leads to better plant coverage. ➢ Reduces environmental impact by lowering active ingredient runoff.	➢ Stability issues like phase separation during storage. ➢ Energy-intensive production processes (e.g., ultrasonication).	Mustafa and Hussein 2020
Case Study:	Citronella-oil (1%) and biosilica (2%) nanoemulsion, and neem oil formulas (1%) effectively suppressed nematode populations (99.33% and 97.65%, and 99.66%, respectively), increasing the sinensetin content/production in comparison with control; and could be evaluated further in the plantation in the field.		Djiwanti et al. 2022
Nano-Metal Oxides (e.g., CuO, ZnO)	- Broad-spectrum activity with antifungal, antibacterial, and insecticidal properties. - Low chance of resistance development due to multiple action modes.	- Potential phytotoxicity and bioaccumulation risks. - Expensive and energy-intensive to produce at scale.	Saqib et al. 2019
Case Study:	CuO nanoparticles inhibited *Pseudomonas syringae* in tomato plants effectively. Another study reported that Pseudomonas syringae was inhibited after exposure to 200 mgL^{-1} of Cu-based NPs without any negative effect on other microbes indicating its selective effect.		Banik and Pérez-de-Luque 2017; Tortella et al. 2024
Nano-Clays	➢ Economical and readily available materials. ➢ Reduces pesticide leaching and improves soil retention. ➢ Environmentally benign.	➢ Limited compatibility with certain active ingredients. ➢ Farmers' unfamiliarity with application techniques.	Margal et al. 2023; Rana et al. 2024
Case Study:	Clay-composite nano-formulations reduced herbicide leaching by 40% in field trials.		

Nanosilver	➢ Highly effective against a wide range of pathogens like bacteria, fungi and some viruses. ➢ Compatible with biocontrol agents. ➢ Long-lasting efficacy.	➢ Risk of toxicity to beneficial microorganisms and aquatic ecosystems. ➢ Expensive production and regulatory challenges.	Zahoor et al. 2021; More et al. 2023
Case Study:	Silver nanoparticles controlled *Alternaria solani* causes early blight on potatoes more effectively than conventional fungicides. Lower concentrations of silver nanoparticles increased phenolics, PO, PPO, and PAL production. These defensive mechanisms clearly demonstrate the fungicidal potential of AgNPs and recommend their utilization in different crop protection programs.		Ansari et al. 2023

Future Directions

Research into nanotechnology applications for use in agriculture especially in the field of crop protection has become increasingly popular over the past decade. This analysis of the latest research trends provides a useful basis for identifying research gaps and future priorities. The development of novel plant-protection products has received greater attention than other applications, such as those related to nanosensors or fertilizers. Remarkable opportunities to renew agriculture practices have been introduced by using nanotechnology-based delivery systems, attributed to the smart controlled release profile of fertilizers and agrichemicals require to enhance crop productivity (Prasad et al. 2017). Such systems play a critical role in agriculture, improving fertilizers and agrochemicals performances (Fraceto et al. 2016). Presently, numerous research initiatives of nanopesticides prioritize performance optimization, including enhancing activity (Li et al. 2022), targeted deposition (Su et al. 2023), improved safety (Gao et al. 2018), and controlled release (Xiao et al. 2022).

However, some nanopesticides might be designed without initial consideration for specific application scenarios or are limited to traditional spraying methods. This research idea contradicts the needs of pesticide application in future diversified agriculture. Furthermore, there is a scarcity of review covering existing nanopesticides developed for diverse agricultural scenarios. It should be noted that the plant cultivation environment is diverse,125 and future application scenarios for pesticides might be more extensive, such as cities, oceans, and even deserts. This is crucial information that developers and manufacturers of nanopesticides must not overlook. As agricultural mechanization advances, pesticide application methods are also evolving. Therefore, this review focuses on ‘Scenario-oriented Nanopesticides', highlighting the importance of prioritizing practical and specific application scenarios in the future development of nanopesticides to enhance sustainable development potential and resource utilization.

In addition to the application methods, experimental research targeting specific scenarios should consider environmental conditions when pests and diseases occur (such as temperature, humidity, and pH) as well as microenvironmental changes within the plant (such as enzymes, ROS and hormones). More importantly, these products need to be validated in the field to bridge the gap between the scientific and industrial circles and provide the public with a more objective and realistic understanding. In addition, it is crucial to consider the environmental impact and biosafety of nanopesticides. Manufactured nanopesticides require a comprehensive evaluation system.126 Scenario-oriented nanopesticides can more accurately target actual production needs and accelerate the industrialization process. In the context of sustainable agriculture, this concept is expected to lead the future development of nanopesticides.

Conclusion

~~Plant diseases that are carried by the soil, such as fungi, bacteria, viruses, and nematodes, can damage a plant's root system and collar, resulting in significant financial loss. Because chemical pesticides are unable to penetrate the soil system and do significant harm to the environment and soil, managing such diseases with traditional methods is challenging. One possible management approach to lessen the threat of soil-borne plant diseases is nanobiotechnology. Because of their many antibacterial characteristics, such as the production of reactive oxygen species (ROS), toxicity from nanoparticles, and destabilization of cell membranes, organelles, and other macromolecules, nanomaterials can be used to control soil-borne diseases. Because of their smaller size and higher surface area to volume ratio, nanoparticles have a higher potential for penetration and better interactions with bacteria that live in soil, which increases the effectiveness of their control. In order to lessen the amount of chemicals that are released into the environment, nanomaterials can also be employed as intelligent pesticide, fungicide, and fertilizer delivery systems. In addition to validating these technologies against current technologies, more study is required to ascertain the viability, sustainability, efficiency, application and releasability of goods based on nanotechnology in real-world.~~

Nanopesticides, as a promising technology, bring scientific and technological impetus to sustainable development and green revolution of agriculture. The excellent physicochemical properties, beneficial biological effects, and functional potential of nanopesticides have significantly contributed to improving utilization rates of pesticides, enhancing pest and disease management, and alleviating stresses. In conclusion, the development and production of nanopesticides will necessarily lead to an increased amount of nanopesticides applied in agriculture. A reliable and comprehensive risk assessment before widespread application is the first line of defense to ensure environmental safety and human health. There have been serious environmental issues, like DDT or neonicotinoids in human history, which were allowed to occur due to lack of a comprehensive assessment of environmental risk in advance. For nanopesticides, we should learn the lesson and avoid a similar outcome in the future. Unexpected risk of nanopesticides comes from their possible toxicity to nontarget organisms, transportation, and bioaccumulation, and from interactions with other pollutants in the environment. These processes should be the focus of the regulatory framework for nanopesticide risk assessment. In order to lessen the amount of chemicals that are released into the environment, nanomaterials can also be employed as intelligent pesticide, fungicide, and fertilizer delivery systems. In addition to validating these technologies against current technologies, more study is required to ascertain the viability, sustainability, efficiency, application and releasability of goods based on nanotechnology in real-world.

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Authors contribution

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agreed to be accountable for all aspects of the work.

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