Bio Vet Innovator Magazine

Volume 1 (Issue 3) SEPTEMBER 2024

Popular Article

Nanoparticles: Tiny but Mighty Tool against Plant Pathogens

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DOI - https://doi.org/10.5281/zenodo.13899225

Received: September 29, 2024

Published: September 30, 2024

Abstract:

Plant pathogens are an unavoidable nuisance to the crops that ultimately hinders the economy of a nation. To manage the plant diseases time to time new methods and technologies are being developed and practiced. Fungicides serve to be one of the most successful management strategies but it comes with some negative aspects like increased pressure on environment and development of resistance in plant pathogens. So new advanced sciences like use of nanoparticles are being utilized as alternate methods to combat plant pathogens. Nanotechnology has the potential to revolutionize disease management in agriculture through the development of nanopesticides. These offer key benefits including improved solubility of poorly water-soluble pesticides, enhanced bioavailability, and reduced toxicity when loaded onto nanoparticles. Nanopesticides also allow for controlled and target-specific delivery, increasing efficacy while minimizing environmental impact. Other advantages include extended shelf-life, pH-dependent release, and smart delivery of RNAi molecules, enhanced UV stability, and rain-fastness. Additionally, nanopesticides offer selective toxicity, improving pest control precision and overcoming pesticide resistance. These innovations position nanoscale materials as critical tools in the agritech revolution, advancing sustainable and effective crop protection.

Keywords: Fungicides, Nanotechnology, Nanopesticides, sustainable, bioavailability

Introduction:

Reduction in crop production is attributed to several biotic and abiotic factors. The biotic factors primarily comprise of pests including insects, mites, birds, rodents and many more; pathogens like bacteria, fungi, virus, nematodes etc. and several kinds of weeds. The abiotic factors include vagaries of nature, environmental constraints and nutritional disorder to name a few. Among these the major constraint in successful crop production is the losses incurred due to biotic agents among which plant pathogens possess a serious and growing threat to the crop cultivation. Crop productivity is severely reduced by plant diseases and pests, which

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are thought to cause annual losses of 20% to 40% worldwide. The use of pesticides, including fungicides, herbicides, and insecticides, is a major component of modern pest management. Despite having numerous benefits, such as being readily available, acting quickly, and being dependable, pesticides can cause harm to non-target organisms, encourage the resurgence of pest populations, and lead to the development of resistance. In addition, it is estimated that 90% of pesticides applied are lost during or following application. Consequently, there's more incentive to create pesticides that are less hazardous to the environment and work well at a lower cost (Ghormade et al. 2011). The solution to this is the start of a new effective domain, i.e., use of nanotechnology and nanoparticles to substantially minimize the hazardous effects of the agro chemicals. Nanotechnology as a growing science in agriculture has immense potential in managing agricultural issues.

Plant diseases pose a serious risk to agricultural output, with an annual economic loss of nearly $220 billion (FAO 2022). Future crop losses are predicted to rise as a result of climate change exacerbating this issue. There are control methods available for managing plant diseases. But the inefficiency of pesticide applications and delivery is a major worry. For instance, according to Pimentel and Burgess (2012), more than 50% of pesticides applied by air do not reach the intended target crops, posing serious risks to the environment, nontarget organisms, and applicators (Schäfer et al. 2019). As a result, new technologies are desperately needed to improve the efficacy and delivery efficiency of pesticides, and nanotechnology offers promise as a means of addressing these inefficiencies.

Nanotechnology For Plant Disease Management:

Information from physics, chemistry, natural science, and other disciplines is incorporated into the flexible field of nanotechnology. The operation or assembly of discrete atoms, molecules, or molecular collections into structures to form material manoeuvres with innovative or incredibly diversified assets is what Joseph and Morrison (2006) defined as nanotechnology. By using cutting-edge tools for prompt infection detection, targeted treatment, enhancing vegetation's capacity to absorb nutrients, preventing contamination and withstanding environmental stresses, and developing dynamic handling plans, among other things, the application of nanotechnology in agriculture has the potential to transform the field. The agronomic production will be assisted by intelligent delivery systems and sensors to combat viral infections and subsequent harvesting.

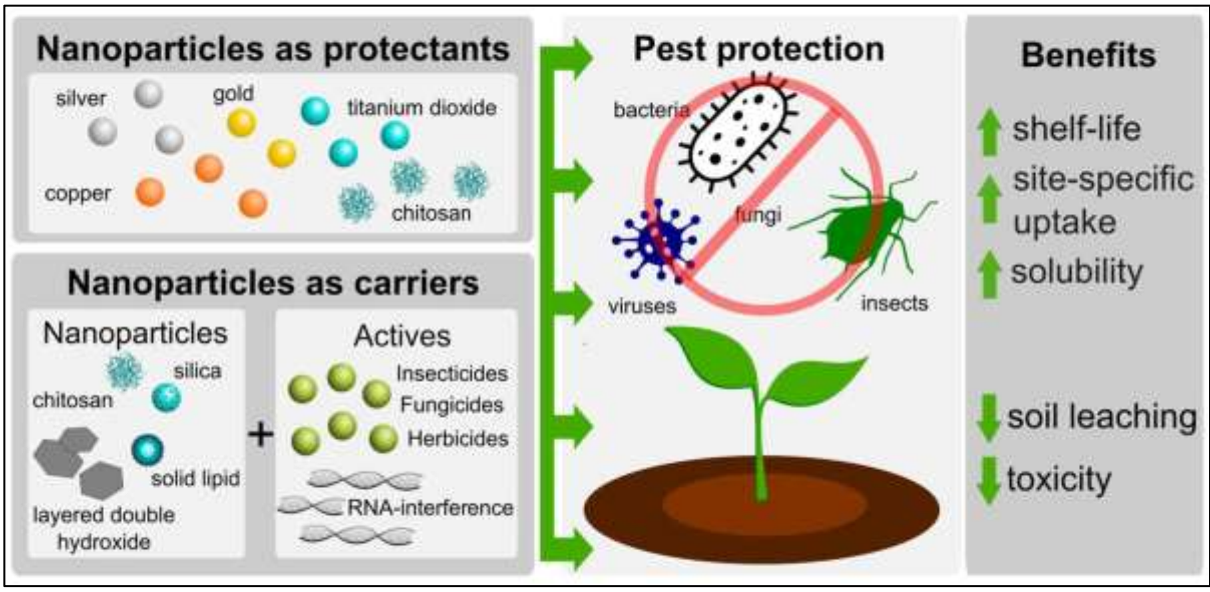

Fig 1: Nano materials as protectants or carriers to provide crop protection (Worrall et al. 2018).

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Nanoparticles As Carriers Against Plant Pathogens:

Nanoparticles are increasingly being used as carriers to enhance the effectiveness of agricultural formulations, such as insecticides, fungicides, herbicides, and RNAi-inducing molecules. These nanoparticles entrap, encapsulate, absorb, or attach active molecules to protect them, improve their solubility, and ensure a controlled release. Silica nanoparticles (e.g., porous hollow silica nanoparticles or mesoporous silica nanoparticles) are widely used due to their customizable size, shape, and structure (Mody et al. 2014). They load pesticides into their inner core, protecting the active molecules from degradation, such as by UV light, and enabling a sustained release. Silica is also known for its role in enhancing plant tolerance to stress, making it a natural choice for pest control formulations. Chitosan nanoparticles are hydrophobic and typically require blending with other materials to improve solubility. Their ability to adhere to plant surfaces, such as leaves and stems, extends the contact time and facilitates the uptake of active molecules. Chitosan's reactive groups allow modifications that enhance its properties as a carrier (Kashyap et al. 2015). Solid lipid nanoparticles (SLNs) are lipid-based and solid at room temperature, serving as a matrix to entrap lipophilic molecules without organic solvents (Ekambaram et al. 2012) However, SLNs have low loading efficiency and may experience leakage of the active ingredient during storage. Despite this, they provide controlled release of active molecules. Layered double hydroxides (LDHs) are clay nanoparticles that trap active molecules between their layers and break down under acidic conditions. These nanoparticles help transport biologically active materials across plant cell walls.

These nanoparticles have been explored as carriers in plant disease management, particularly for fungicides. Research on nanofungicides has demonstrated that nanoparticle formulations can improve the stability and water solubility of active ingredients, reduce volatilization, and provide slow, sustained release of fungicides. Studies have shown that nanoparticle-based formulations can be as effective, or even superior, to conventional fungicides, particularly when protecting against decay or infection over long periods. For instance, tebuconazole, a fungicide, was successfully loaded into bacterial ghosts, increasing its adherence to plant surfaces and enhancing its performance against fungi under rain conditions. Pyraclostrobin, another fungicide, was loaded onto chitosan-lactide nanoparticles, showing enhanced inhibition of fungal pathogens over time. Nanoparticles have also been used to encapsulate essential oils with antifungal properties, enhancing their stability and antifungal activity over extended periods. Studies have demonstrated that encapsulating fungicides like chlorothalonil and tebuconazole into nanoparticles significantly reduces the amount of active material required while maintaining efficacy. For example, nanoparticle-loaded fungicides were able to protect wood from fungal decay with reduced application rates. Nanoparticles have also shown promise in reducing pesticide leaching in soils, improving soil retention of active ingredients, and minimizing environmental contamination. Slow-release nanoparticle formulations, such as calcium carbonate carrying validamycin, have been shown to improve long-term efficacy compared to the active ingredient alone. Research on the distribution and dissipation of pesticide-loaded nanoparticles in plants has shown minimal accumulation in edible parts, highlighting the potential safety of nanoformulations for agricultural use (Liu et al. 2002).

Nanoparticle And Their Use Against Plant Pathogens:

The first nanoparticle (NP) investigated for plant disease management was silver (Ag). Several studies, including those by Park et al. (2016), focused on the early use of silver nanoparticles (Ag NPs) to control powdery mildew, all of which demonstrated significant disease suppression. Lamsal et al. (2011) reported that a concentration of 100 μg/mL provided control comparable to conventional fungicides and showed a curative effect. Further research has supported the effectiveness of Ag NPs in combating fungal pathogens, bacteria, and nematodes.

Copper nanoparticles (NP Cu) were a natural choice for plant disease management due to their long-standing use as contact bactericides and fungicides. However, serious research into NP Cu for disease control didn't begin until 2013, when foliar applications of NP CuO, Cu_2O, and Cu/Cu_2O composites were compared to conventional copper fungicides for managing late blight caused by Phytophthora infestans (Giannousi et al. 2013). Among the treatments, NP CuO at concentrations of 150–340 μg/mL showed superior performance. Since then, more advanced and refined Cu NP composites have been developed. For example, there was a novel approach introduced using engineered copper NP composites with core-shell structures, multivalent copper, and fixed quaternary ammonium copper for managing bacterial spot caused by copper-resistant Xanthomonas perforans. Additionally, the use of Cu as a nanofertilizer to enhance disease resistance has been explored across various plant-disease systems, including asparagus with Fusarium crown and root rot, chrysanthemum with Fusarium wilt, eggplant with Verticillium wilt, soybeans with sudden death syndrome, tea with red root rot, tomato with Fusarium wilt, and watermelon with Fusarium wilt (Elmer et al. 2018).

Zinc nanoparticles (Zn NPs) have been known to possess antibacterial activities against a range of fungal diseases, bacteria, and viral illnesses. Nonetheless, there are still few field studies demonstrating a discernible decrease in illness. Zinc nanoparticles (Zn NPs) have been used to control Fusarium graminearum in sorghum, Cercospora leaf blight in sugar beetroot and bacterial leaf spot on roses. ZinkicideTM, a zinc-based nanoproduct, is presently pending registration to be used in the management of citrus canker, which is caused by Xanthomonas citri subsp. citri. According to field trials, ZinkicideTM was more successful than conventional bactericides like cuprous oxide (Cu_2O) and blends of cuprous oxide and zinc oxide (Cu_2O/ZnO) in reducing the occurrence of disease. Furthermore, ZinkicideTM treatments were observed to be efficacious in inhibiting melanose (Diaporthe citri) and citrus scab (Elsinoe fawcetti) on grapefruit (Graham et al. 2016).

Sulphur (S), aluminium oxide (AlO), magnesium oxide (MgO), titanium oxide (TiO), and ceO have all shown promise in controlling plant diseases in a variety of systems. The majority of research has connected the application of these nanoparticles to specific adjustments in the defence systems of the host plant. Furthermore, these elements' nanoparticle forms were typically more effective at promoting plant health than their bulk or salt forms, frequently requiring much less of the active metal to achieve the same or superior results (Elmer et al. 2018).

Nanoparticles And RNAi Against Plant Pathogens:

The RNA interference (RNAi) pathway presents a promising method for managing plant pathogens. RNAi, a natural defense mechanism in plants, is triggered by double-stranded RNA (dsRNA), which is processed into small interfering RNA (siRNA) by Dicer-like enzymes. These siRNAs guide RNA-induced silencing complexes (RISCs) to degrade pathogen RNA, preventing its translation and curbing infection. While RNAi was initially deployed via genetic modification, concerns over genetically modified organisms (GMOs) have spurred research into alternative delivery methods, such as topical applications of dsRNA. However, topical dsRNA faces challenges like environmental degradation and poor uptake by target pathogens. To improve effectiveness, nanoparticles are being explored as carriers of RNAi-inducing molecules. Nanoparticles such as LDH (layered double hydroxide) have been used to protect plants from viral pathogens. For example, a single spray of dsRNA-loaded LDH nanoparticles, called BioClay, protected plants from cucumber mosaic virus (CMV) and pepper mild mottle virus (PMMoV) for 20 days, even affecting new leaves. This highlights the potential of nanoparticle-assisted RNAi for managing plant pathogens. In another study, dsRNA delivered via nanoparticles was shown to be successfully absorbed through plant roots, inducing gene silencing in Arabidopsis. These advances suggest that nanoparticles can enhance the stability and delivery of RNAi-based treatments, offering a novel approach for protecting crops from viruses, fungi, and other pathogens (Thairu et al. 2017).

Conclusion:

Nanotechnology is becoming an increasingly vital tool in plant disease management, with engineered nanoparticles (NPs) being used as both bactericides and fungicides, as well as nanofertilizers to boost plant health. So far, the majority of research has focused on the antimicrobial properties of nanoparticles, particularly those of silver (Ag), copper (Cu), and zinc (Zn), and their ability to enhance plant defense responses. Nanoparticles are expected to play a key role in suppressing plant diseases in both greenhouse and field environments. One significant benefit of using nanotechnology in plant disease management is the considerable reduction in the amount of active metals entering the ecosystem, as compared to conventional metal-based fungicides. However, a challenge in applying nanotechnology to plant pathology is that nanoparticles often behave differently across various plant-pathogen systems, necessitating a tailored approach for each specific disease. Additionally, nanomaterials tend to aggregate over time, which reduces their efficacy, thus requiring ongoing innovation in the development of new nanocomposites and formulations. Chemists will play a crucial role in overcoming these challenges by designing nanoparticles that remain stable and effective in diverse environments. With the pressing challenges faced by modern agriculture, the development and deployment of nano-enabled strategies for disease suppression are poised to be critical tools in ensuring and sustaining global food security.

Acknowledgment:

The authors are grateful to Dr. Y S Parmar University of Horticulture and Forestry, Nauni, Solan (HP) for providing all facilities for the writing the article.

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