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Nanotechnology in disease and pest management of vegetables

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Abstract: -

Modern agriculture faces growing challenges, including pest resistance, soil degradation, and the impact of climate change, all of which threaten crop productivity. To address these issues, nanotechnology is emerging as a game-changer in pest and disease management. Nanomaterials such as silver (AgNPs), copper (CuNPs), and zinc oxide (ZnO) nanoparticles have shown remarkable potential in controlling fungal, bacterial, and viral infections, as well as insect pests. Their nanoscale properties enhance pesticide efficiency, improve plant protection, and reduce environmental residues. This article explores how nanotechnology is being applied in agriculture, detailing its effectiveness in plant disease and pest control. Additionally, it highlights various nanopesticides currently available on the market, showcasing their composition and role in sustainable farming. However, despite their advantages, concerns about nanomaterials' safety and environmental impact persist. Issues such as toxicity, accumulation in soil and plants, and potential effects on beneficial organisms require thorough investigation. Adopting eco-friendly "green synthesis" techniques offers a promising way to minimize these risks while maintaining effectiveness. With responsible research, careful regulation, and sustainable application, nanotechnology has the potential to revolutionize pest management. By reducing reliance on conventional chemicals and promoting safer alternatives, it paves the way for a more resilient and eco-friendly agricultural future.

Keywords: - *nanomaterial, control, Agricultures, plant pathogens, viral, bacterial*

Introduction

Agriculture is the cornerstone of global food security and human survival, yet the persistent challenge of managing vegetable pests and diseases continues to threaten productivity. Additionally, climate change-induced factors such as prolonged droughts, soil degradation, and inefficient nutrient uptake further exacerbate these agricultural

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constraints. In response, nanotechnology has emerged as a transformative approach to addressing these pressing issues. Due to their unique physicochemical properties, nanomaterials exhibit distinct advantages over their bulk counterparts, enabling innovative applications in plant protection.

One of the most critical concerns in modern agriculture is the increasing resistance of pests and pathogens to conventional control methods, making their management increasingly difficult. Nanomaterials have demonstrated promising potential in mitigating these threats, given their ability to interact with and suppress a wide range of agricultural pests and pathogens through diverse mechanisms. This article examines the role of nanomaterials in managing major plant pathogens and insect pests that significantly impact vegetable production worldwide. Their efficacy is largely dependent on multiple factors, including their composition, particle size, structural morphology, and administered dosage. Notably, optimized nanomaterial-based treatments have exhibited positive effects on plant health, promoting growth and improving overall crop performance.

Furthermore, recent research has highlighted the potential of nanotechnology in controlling plant viral infections, which constitute a major threat to global vegetable output. Bacterial diseases pose a significant threat to agriculture, causing severe yield losses. *Ralstonia solanacearum*, for example, can devastate potato crops by over 90% (Government of Western Australia, 2019). With rising resistance to traditional bactericides, nanotechnology offers a promising alternativeThis discussion extends to the effectiveness of nanomaterials in managing common agricultural pests while exploring their underlying mechanisms of action. Evidence suggests that nanomaterials operate through multiple pathways, exerting targeted effects on harmful organisms. However, establishing a balance between their beneficial applications and potential toxicity remains a challenge. The extent of toxicity varies across different plant species, necessitating comprehensive risk assessments before their large-scale implementation.

Nanosensors, a breakthrough in nanotechnology, are revolutionizing agriculture by making pest control and crop quality management more efficient (dos Santos *et al*., 2021). These tiny yet powerful tools don’t just detect issues early they do so with incredible speed and accuracy. Whether it's identifying pollutants, monitoring environmental changes, or spotting diseases and pests before they spread, nano sensors provide farmers with real-time insights, allowing for timely interventions and healthier crops.

While nanotechnology offers substantial promise in plant protection, several challenges remain, including regulatory limitations, safety concerns, and commercialization barriers. This review provides insights into recent advancements, existing challenges, and future prospects for the integration of nanomaterials into sustainable agricultural practices.

Nanomaterials against fungal disease

Fungal pathogens are among the most destructive causes of plant diseases, responsible for nearly 85% of infections. To combat them, farmers rely heavily on chemical fungicides, often applying high doses throughout crop growth. However, overuse has led to growing resistance, making traditional fungicides less effective (Rejali *et al*., 2022). Nanotechnology offers a promising alternative, with research showing that silver nanoparticles (AgNPs) can effectively suppress fungal infections. For instance, AgNPs synthesized using white radish extracts inhibited fungal growth by 50–90% in *Fusarium* and *Penicillium* species (Ali *et al*., 2015). Similarly, AgNPs helped protect *Phytophthora*-infected tobacco plants, boosting survival rates to 96.3% at optimal doses. They also damaged fungal mycelia in several other plant pathogens. Other nanomaterials, such as carbon nanotubes and copper oxide nanoparticles, have also shown strong antifungal activity, particularly in post-harvest settings where fungal infections thrive during transport and storage (Hao *et al*., 2017).

Nanomaterials against viral disease

Silver nanoparticles (AgNPs)also demonstrated antiviral activity against *Sunhemp rosette virus* (SHRV), preventing lesion formation in infected plants. Similarly, Fe_2O_3 and TiO_2 nanoparticles, along with multi-walled carbon nanotubes (MWCNTs), enhanced plant defense against TuMV, increasing shoot biomass and reducing viral protein synthesis. Carbon-based nanomaterials (C60 and CNTs) restricted TMV spread, lowering viral coat protein transcripts by over 70%. ZnO nanoparticles also inhibited TMV replication by triggering defense-related enzymes and hormone production (Cai *et al*., 2019). For *Papaya ringspot virus* (PRSV), SiO_2 nanoparticles mitigated symptoms in cucumber plants, reducing viral accumulation (Elsharkawy & Mousa, 2015). AgNPs showed selective effectiveness against *Bean Yellow Mosaic Virus* (BYMV), preventing symptoms when applied post-infection (Elbeshehy *et al*., 2015).

Elsharkawy, M. M., & Mousa, K. M. (2015). Induction of systemic resistance against Papaya ring spot virus (PRSV) and its vector Myzus persicae by Penicillium simplicissimum GP17-2 and silica (SiO2) nanopowder. *International journal of pest management*, *61*(4), 353-358.

Nanomaterials against bacterial disease

Silver nanoparticles (AgNPs) have effectively controlled bacterial infections, such as soft rot in peppers, reducing disease severity to just 15% (Ayisigi *et al*., 2020). A nanocomposite of cellulose, starch, and poly (D, L-lactide-co-glycolide) also exhibited prolonged antibacterial effects against *Pseudomonas syringae* in tomatoes without harming plant growth.

Copper oxide nanoparticles (CuO NPs) outperform traditional copper treatments, inhibiting *Ralstonia solanacearum* and *Erwinia amylovora* more effectively (El-Batal *et al*., 2020). Additionally, titanium dioxide (TiO_2) and magnesium oxide (MgO) nanoparticles have demonstrated strong bactericidal properties, disrupting membranes and triggering plant immune responses (Cai *et al*., 2018). ZnO NPs also reduce bacterial viability and biofilm formation, significantly inhibiting *Dickeya dadantii* (Hossain *et al*., 2019).

Nanomaterials against insect pests

Nanotechnology offers innovative solutions for pest management, leveraging nanomaterials' unique properties to enhance insecticidal efficacy. Pests cause significant agricultural losses, with damage estimates reaching 50% in crops like cotton (Dhaliwal *et al*., 2010). Silver nanoparticles (AgNPs) disrupt gastropod digestion, while silica-based nanocarriers improve insecticide delivery, effectively controlling rice pests *Cnaphalocrocis medinalis* and *Chilo suppressalis* (Gao *et al*., 2020). Stored-product pests, such as *Tribolium castaneum* and *Sitophilus oryzae*, show high susceptibility to nanoparticle treatments. PEG-coated essential oil nanoparticles and Plantago-derived nanoliposomes prolong effectiveness (Khoshraftar *et al*., 2020). Chitosan-based nanocarriers enhance insecticide efficiency against *Myzus persicae* and *Spodoptera litura*, extending bioactivity and reducing application frequency (Kang *et al*., 2012).

Metal oxide nanoparticles (TiO_2, ZnO, Al_2O_3) exhibit potent larvicidal and ovicidal properties, with ZnO formulations significantly reducing *Callosobruchus maculatus* fecundity (Malaikozhundan & Vinodhini, 2018). Encapsulated acephate nanoparticles achieve complete mortality in *S. litura* and *Oligonychus coffeae*, outperforming conventional formulations (Pradhan *et al*., 2013). AgNPs also show strong insecticidal activity against *Rhyzopertha dominica* and *S. oryzae* (Vadlapudi & Amanchy, 2017). These findings highlight nanomaterials' potential as advanced, efficient pest control agents.

Challenges in Using Nanomaterials for Pest Control

Various products available in the market				
Product Name	**Company**	**Country**	**Composition**	**Function**
Nano Guard	Vision Mark Biotech	India	Nanoemulsion of plant extracts (<200 nm)	Broad-spectrum pesticide, non-toxic, residue-free
Nano Agro Total	NanoScoping	Brazil	Biodegradable nanoparticles, vegetable oils	Antifungal, antibacterial, repellent
Tropical Agrosystem Pesticides	Tropical Agrosystem	India	Nanoemulsions of natural extracts	Controls caterpillars, ants, mites
Agrilife Nanopesticides	Agrilife	India	Silver nanoparticles (AgNPs)	Controls fungal, bacterial, and viral diseases; combats insect pests
Nanosept Products	Nanosept	-	Silver nanoparticles (AgNPs)	Broad-spectrum antimicrobial agents
Kanak Biotech Products	Kanak Biotech	-	Silver nanoparticles (AgNPs)	Pathogen control
Bio Nano Tech Fungicides & Bactericides	Bio Nano Tech	-	Copper nanoparticles (CuNPs)	Fungicidal and bactericidal properties

(dos Santos *et al.*, 2024)

While nanomaterials offer promising solutions for pest control, they come with their own set of challenges that need careful consideration:

- **Balancing Effectiveness and Safety: -** Pesticides are inherently toxic, which is why their use is tightly regulated. Nanomaterials can help by making pesticides more efficient at lower doses, reducing their harmful impact. However, it's equally important to assess whether the nanomaterials themselves pose risks to humans, plants, or the environment.
- **Unintended Effects on Plants and Growth:** - Some nanomaterials can accumulate inside plant cells and even cause genetic damage. Their influence on plant health can vary, potentially affecting:
  - Seed germination and overall growth.
  - Root and sprout development.
  - Photosynthesis and water uptake, which are crucial for plant survival.
- **Finding the Right Balance of Dose and Exposure:** -The effects of nanomaterials

depend heavily on how much is used and for how long. If applied correctly, they can enhance pest control without harming the crops but improper use might lead to unintended consequences.

- **Impact on Soil Health and Microbial Life:** -Since nanomaterials can affect a wide range of organisms, their impact on soil microbes and beneficial insects must be carefully studied. Healthy soil life is essential for sustainable farming, and any disruption could have long-term consequences.
- **Ensuring Crop Quality and Safety: -** Nanomaterials can improve pest resistance, but they may also affect the quality of the food we grow. Scientists need to carefully monitor how these materials interact with plants to ensure they remain safe for consumption.
    - **The Promise of Green Synthesis: -** One way to make nanomaterials safer is by using "green synthesis" methods, which avoid toxic solvents and harmful byproducts. This approach not only reduces environmental risks but also makes nanotechnology more sustainable for future agricultural use.

By addressing these challenges, researchers can work towards making nanotechnology a safer and more effective tool for modern farming.

Conclusion

Nanotechnology is reshaping modern agriculture by offering innovative ways to manage pests and diseases more effectively. With their unique properties, nanomaterials provide a promising alternative to traditional chemical treatments, helping to control fungal, bacterial, viral, and insect threats while also supporting healthier crop growth. Their ability to enhance pesticide efficiency and reduce chemical residues makes them a valuable tool in sustainable farming. However, their widespread use comes with challenges. The potential risks of nanomaterials such as toxicity concerns, environmental impact, and long-term effects on soil health must be carefully evaluated. Striking a balance between effectiveness and safety is crucial. Scientists and policymakers need to conduct thorough research to ensure nanotechnology benefits agriculture without unintended consequences. Green synthesis methods, which use eco-friendly processes to create nanomaterials, offer a promising way to reduce potential risks. Looking ahead, nanotechnology has the potential to revolutionize farming by improving pest control, reducing reliance on harmful chemicals, and boosting food security. To fully harness its benefits, ongoing research, responsible regulation, and collaboration between researchers, farmers, and industry leaders will be essential. By addressing the challenges and refining its applications, nanotechnology can pave the way for a more sustainable and productive agricultural future.

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