Deep Science Publishing
https://doi.org/10.70593/978-93-49307-12-4_6

Chapter 6

Nano-Formulated Pesticidal Constructs: Eco-Conscious Strategies for Phytopathogenic Containment

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Abstract: Nano-formulated pesticidal constructs represent a revolutionary approach to managing phytopathogens while minimizing environmental impact. These advanced formulations leverage nanotechnology to enhance pesticide efficiency, improve target specificity, and reduce off-target effects. Encapsulation techniques using nanocarriers such as liposomes, polymeric nanoparticles, and metal-based nanostructures ensure controlled release, prolonged efficacy, and reduced chemical residues in the ecosystem. By optimizing bioavailability and penetration into plant tissues, these nano-pesticides effectively combat fungal, bacterial, and viral pathogens while mitigating toxicity to non-target organisms. Moreover, their eco-conscious design aligns with sustainable agricultural practices, reducing the excessive use of conventional pesticides and mitigating soil and water contamination. Future research aims to refine nano-pesticidal formulations for greater biocompatibility and regulatory acceptance, ensuring their role in next-generation plant protection strategies. The integration of nanotechnology in plant pathology presents a promising avenue for enhancing crop health, productivity, and environmental stewardship.

Keywords: Nanopesticides, sustainable agriculture, promising shift**,** challenges

Citation: Kumari, B., Kumar, P., Singh, A. P. & Singh, K. K. (2025). Nano-Formulated Pesticidal Constructs: Eco-Conscious Strategies for Phytopathogenic Containment. In *Eco-Friendly Nanotechnology: Harnessing Small-Scale Technologies for a Cleaner and Healthier Planet* (pp. 84-94). Deep Science Publishing. https://doi.org/10.70593/978-93-49307-12-4_6

1 Introduction

The Nano-pesticides represent an innovative class of crop protection chemicals that leverage the unique properties of nanotechnology to enhance pesticide delivery, improve efficacy, and reduce environmental and human health risks. These formulations incorporate nanoparticles, typically ranging from 1 to 100 nm in size, which offer remarkable advantages over traditional pesticide formulations. Nano-pesticides are designed to improve the precision of active ingredient delivery, enhance their solubility, and facilitate more controlled release over time, all of which contribute to more sustainable agricultural practices (Kah & Hofmann,2014; Wang *et al.*, 2022). The selection of nano bio-pesticides has various important points for consideration, like they should be easy to prepare, economically viable, effective against a wide range of pests, must be safer to non-target organisms as well as the environment, non-toxic, should not accumulate in the food chain, should have nil or negligible residues, should not affect the quality of food, fragrance, texture, and flavour, and should be easy availability for application (Lade et al, 2017). Generally, for improvement of efficacy, better solubility, and a slower rate of release and degradation, the traditional methods for the preparation of synthetic pesticides are blended (Nuruzzaman *et al.*, 2016).

Similarly, for the formation of nano bio-pesticides, the biological compounds having pesticidal properties serve as capping and reducing agents and are blended with silver salt (Lade et al, 2017). Biologically synthesized NPs differ from chemically synthesized NPs in terms of their activities and effects on insect pests and plants. Due to the large surface area present in NPs, they can bond to other compounds quickly and can circulate easily in the lepidopteran insect's system (Sun *et al.*, 2022). Studies reported that nanocarrier materials with plant secondary metabolites cause indigestion, and collapse the water protection barrier ultimately resulting in the death of insects (Nuruzzaman *et al.*, 2016).

Liu and Xing (2007) discussed different types of nanomaterials (nanotubes, Al, ZnO, Zn, and multi-walled carbon) that did not show any adverse effect on five different vegetables and ryegrass during seed germination and termination of root elongation. For corn plants treated with oleic acid and nanocapsules separately, Psquoto-Stgliiani et al. (2017) observed a negative effect on the physiological parameters against oleic acid, while there was no phytotoxic effect for nanocapsules.

2 Mechanisms of Action of Nano-pesticides

Nano-pesticides exhibit unique mechanisms of action, including enhanced adhesion to plant surfaces, controlled release of active ingredients, and improved penetration into target pests. Some nano-formulations facilitate selective toxicity by functionalizing nanoparticles with ligands that bind to specific biological targets in pests, minimizing harm to non-target organisms. Additionally, nano-pesticides can exploit mechanisms such as reactive oxygen species (ROS) generation, cellular membrane disruption, or interference with pest metabolism, leading to improved pest control efficacy with reduced chemical usage.

2.1 Enhanced Targeting and Penetration

Nanoparticles, due to their small size, can penetrate the cuticle and cell walls of plants more easily than conventional pesticide molecules. This increased penetration allows the pesticide to reach deeper tissues of the plant, ensuring more effective pest control, particularly for internal plant pathogens or insect pests that typically evade treatment. Studies have demonstrated that polymeric and mesoporous silica nanoparticles improve the solubility and stability of hydrophobic pesticides, enhancing their uptake through plant roots and leaves (Tong *et al.,* 2017). This facilitates systemic movement within the plant, increasing the pesticide's effectiveness against hidden pests and diseases. Additionally, confocal microscopy and elemental detection studies confirm that nanoparticles can be absorbed and translocated through the plant's vascular system, reaching target sites more efficiently than traditional formulations (Xiong *et al.,* 2024). Furthermore, nanocarriers such as silica-based systems have been shown to enhance foliar pesticide uptake, allowing for better translocation and retention in plant tissues, which is crucial for targeting pests like piercing-sucking insects that feed on plant sap (Bueno *et al.,* 2022; Wang *et al.,* 2025). The size and composition of nanoparticles also play a critical role in their efficiency, as studies indicate that optimized mesoporous silica structures enable controlled pesticide release, reducing environmental losses and increasing application precision (Xu *et al.,* 2021). These advancements highlight the potential of nanotechnology in agriculture by improving pesticide efficiency, reducing the required application doses, and minimizing environmental contamination.

2.2 Controlled Release and Sustained Activity

One of the most significant benefits of nano-pesticides is their ability to provide a slow and controlled release of active ingredients. Nanoparticles can be designed to release pesticides over a specific period, ensuring continuous pest protection while reducing the need for frequent applications (Kah *et al.,* 2013). This controlled-release mechanism enhances pesticide stability and minimizes environmental contamination by reducing leaching into groundwater (Kumar *et al.,* 2017). Additionally, it lowers the risk of exposure to non-target organisms, making nano-pesticides a more sustainable alternative to conventional formulations (Rai *et al.*, 2022).

2.3 Increased Stability and Solubility

Many conventional pesticides suffer from poor stability or low solubility in water, limiting their effectiveness and increasing environmental risks due to runoff and accumulation in non-target areas. Nano-pesticides, however, offer a promising alternative by enhancing the solubility and bioavailability of active ingredients, allowing for more efficient distribution and uptake in target organisms. Additionally, nanoparticle-based formulations can protect the active ingredient from premature degradation caused by environmental factors such as light, heat, and microbial activity, thereby extending the pesticide's shelf life and maintaining its potency over time (Kah *et al.*, 2018; Kumar *et al.*, 2019).

2.4 Multifunctional Nano-particles

Beyond just pesticide delivery, some nanoparticles are engineered with dual or even multiple functionalities, making them highly versatile in modern pest management strategies. For example, certain nanoparticles can be designed to carry both fungicides and insecticides simultaneously, allowing a single application to target multiple pests, thereby reducing the need for repeated pesticide use and minimizing environmental contamination (Kah *et al.*, 2018). Additionally, some nano-formulations incorporate features such as UV protection, which helps prevent the degradation of active ingredients when exposed to sunlight, prolonging their efficacy in the field (Shang *et al.*, 2019). Other nanoparticles possess inherent antimicrobial properties, providing added protection against plant pathogens and improving crop resilience against diseases (Ghormade *et al.*, 2011). These multifunctional nano-pesticides not only enhance pest control efficiency but also contribute to sustainable agricultural practices by reducing chemical inputs, lowering application frequency, and mitigating pesticide resistance in target organisms.

3 Benefits of Nano-pesticides for Sustainable Agriculture

3.1 Reduction in Pesticide Usage

Nano-pesticides reduce pesticide usage through enhanced efficiency, precision targeting, and controlled release mechanisms. Traditional pesticides suffer from volatilization and leaching, requiring excessive application. Nano-pesticides improve adhesion, penetration, and site-specific action, minimizing non-target effects on beneficial organisms (Kah *et al.,* 2018; Chhipa, 2017). Nano-encapsulation enables slow release, reducing reapplication frequency and environmental contamination (Shang *et al.,* 2019; Hussain *et al.,* 2021). Additionally, prolonged exposure at effective doses helps prevent pesticide resistance (Kumar *et al.,* 2019). Overall, nano-pesticides support sustainable pest management by lowering chemical inputs, reducing ecological disruption, and promoting agricultural sustainability.

3.2 Minimized Environmental Impact

Traditional pesticides contribute to environmental pollution by contaminating soil, water, and air, leading to bioaccumulation and harming non-target organisms, including beneficial insects and aquatic life (Sharma *et al.,* 2019). Nanopesticides address these concerns by reducing the overall chemical load through enhanced precision targeting, ensuring active ingredients reach only intended pests (Kah *et al.*, 2018). Their controlled release mechanisms enable gradual, sustained pesticide delivery, minimizing excessive accumulation in ecosystems (Shang *et al.,* 2019). Nanoformulations adhere better to plant surfaces and soil particles, reducing leaching and runoff into water bodies (Hussain *et al.,* 2021). Some nanoparticles, such as biodegradable polymers, degrade into non-toxic byproducts, further decreasing environmental persistence (Campos *et al.,* 2019). By improving pesticide efficiency and minimizing ecological disruption, nano-pesticides offer a more sustainable pest management approach, helping reduce agriculture's environmental footprint while maintaining effective pest control and promoting agroecosystem resilience.

3.3 Targeted Pest Control and Selectivity

One of the major advantages of nano-pesticides over conventional products is their ability to selectively target pests. Nanoparticles can be functionalized with ligands or molecular markers that bind specifically to the pest's biology (e.g., enzymes, proteins, or receptors). This ensures that only the target pest is affected, leaving beneficial organisms, such as pollinators and natural predators, largely unaffected (Kah *et al.,* 2018). Additionally, nano-pesticides can be used in conjunction with precision agriculture technologies, such as drones or sensors, to monitor pest populations and apply the pesticide only where needed, further reducing unnecessary pesticide use (Gogos *et al.*, 2012; Bhagat *et al.,* 2022). By integrating these advanced technologies, nano-pesticides contribute to a more sustainable and environmentally friendly approach to pest management.

3.4 Reduced Risk of Pest Resistance

The controlled release of nano-pesticides provides an opportunity to address the growing issue of pest resistance. Traditional pesticide use often leads to the development of resistance due to the high and frequent doses applied, which can overwhelm natural pest defense mechanisms. Nano-pesticides, with their sustained release profiles and targeted action, ensure that pests are exposed to consistent, sub-lethal doses of pesticide over time, which can reduce the likelihood of resistance development (Kah *et al.,* 2018). Moreover, the reduced amount of pesticide applied diminishes the evolutionary pressure that promotes resistance in pest populations (Kumar *et al.,* 2019; Ishtiaq *et al.,* 2022). By maintaining an effective concentration of active ingredients over an extended period, nano-pesticides offer a more sustainable approach to pest management, helping to prolong the efficacy of existing chemical controls while reducing the need for new pesticide development.

3.5 Increased Crop Yield and Food Security

By offering more efficient pest control with fewer applications, nano-pesticides contribute to healthier crops, reducing pest-induced damage and the risk of crop loss. This, in turn, leads to higher crop yields, which is critical for improving food security, especially in regions where pests are a major constraint on agricultural productivity (Kah *et al.,* 2018). In countries where pesticide resistance is rampant, nano-pesticides provide an opportunity to restore effective pest control methods, helping to safeguard food supplies (Kumar *et al.,* 2019; Rani *et al.,* 2021). The ability of nano-formulations to enhance pesticide stability and bioavailability ensures prolonged pest suppression, reducing the frequency of applications and minimizing disruptions to ecosystems, making them a promising tool for sustainable agriculture.

4 Challenges in the Use of Nano-pesticides

4.1 Toxicological Concerns

Despite their potential benefits, the use of nanoparticles raises significant concerns about toxicity, both for humans and the environment. Nanoparticles can exhibit unique properties due to their small size, such as increased bioavailability, which can lead to unanticipated toxicity when interacting with living organisms (Kah *et al.,* 2018). The potential for nanoparticles to accumulate in the soil, water, or food chain is a major concern, as long-term exposure could lead to harmful effects on non-target organisms, including beneficial microbes, pollinators, and even human health (Servin & White, 2016). Additionally, the persistence and transformation of nano-pesticides in the environment remain largely unknown, necessitating further research on their degradation pathways and long-term ecological impacts (Pulit-Prociak & Banach, 2016). Comprehensive studies on the environmental fate, accumulation, and degradation of nano-pesticides are crucial to assess their risks and develop regulatory frameworks that ensure their safe use in agriculture.

4.2 Regulatory and Approval Framework

The regulatory landscape for nano-pesticides is still evolving. Due to the novel nature of nanotechnology, current pesticide regulations often fail to adequately address the unique characteristics and potential risks of nano-formulations (Kah *et al.,* 2018). Regulatory bodies, such as the U.S. Environmental Protection Agency (EPA) and the European Food Safety Authority (EFSA), are working to create appropriate safety standards, testing protocols, and approval processes for nano-pesticides, ensuring their safe use while maximizing their benefits (Howard *et al.*, 2019). However, the lack of universally agreed-upon guidelines may delay the adoption of these technologies, particularly in countries with strict pesticide regulations or limited regulatory infrastructure (Grillo *et al.,* 2021). Coordinated international efforts are needed to develop standardized frameworks that address nano-specific risks while facilitating responsible innovation in agricultural pest management.

4.3 High Production Costs

The synthesis and formulation of nanoparticles often involve complex processes that are more expensive than the production of traditional pesticides. The increased cost of producing nano-pesticides could limit their accessibility, particularly for smallholder farmers in developing countries who may already struggle with the high costs of conventional pesticides (Kah *et al.,* 2018). While the reduced need for frequent applications could offset some of the cost, the initial high cost of nano-pesticides remains a barrier to widespread adoption (Sharma *et al.,* 2019). Additionally, the need for specialized infrastructure, regulatory compliance, and technical expertise further contributes to the overall expense, potentially slowing down commercialization and large-scale implementation, especially in resource-limited settings (Ghormade *et al.*, 2011). Addressing these challenges through cost-effective synthesis methods and policy incentives will be crucial to ensuring that nano-pesticides can benefit both large-scale and smallholder agricultural systems.

4.4 Lack of Long-Term Environmental Data

There is still a significant gap in knowledge about the long-term environmental effects of nano-pesticides. Their behaviour in soil and aquatic ecosystems, their degradation rates, and their potential to bioaccumulate in food webs are all areas requiring more research (Kah *et al.,* 2018). The long-term persistence of nanoparticles in the environment and their potential to affect non-target organisms over time is a key area of concern that needs to be addressed to ensure the sustainability of their use (Xu *et al.,* 2020). Studies have shown that nanoparticles may alter microbial communities, affect soil fertility, and even pose risks to higher trophic levels if they accumulate in plants or enter the food chain (Bundschuh *et al.,* 2018). More comprehensive, long-term studies are necessary to fully assess the environmental risks associated with nano-pesticides and to develop mitigation strategies that minimize unintended ecological impacts.

5. Future Directions for Nano-pesticides in Agriculture

The future of nano-pesticides lies in the continued development of biocompatible and biodegradable nanoparticles that minimize long-term environmental impact while maintaining their efficacy (Kookana, 2014; Tyagi *et al.,* 2023). Advances in precision agriculture will also play a crucial role, with technologies like drones, remote sensing, and GPS-guided spraying systems enabling highly targeted application of nano-pesticides (Parisi *et al.,* 2020). The integration of nano-pesticides with genetically engineered crops or biological control agents could further enhance pest management strategies, providing multi-layered defense systems that reduce dependency on synthetic chemicals (Kumar *et al.,* 2019). Additionally, multidisciplinary research combining nanotechnology, environmental science, toxicology, and plant biology will be crucial in addressing safety concerns and advancing the field (Chaudhary *et al.,* 2022). Collaborations between the public and private sectors, as well as international organizations, will be necessary to develop regulatory frameworks that ensure the safe use of nano-pesticides while promoting innovation and sustainable agricultural practices.

Conclusions

Nano-pesticides represent a substantial development in agricultural pest management, enabling greater efficiency, focused action, and potential environmental benefits. Their capacity to improve pesticide solubility, stability, and controlled release mechanisms permits lower treatment rates while preserving or even boosting efficacy. This, in turn, lowers chemical runoff, mitigates non-target toxicity, and encourages more sustainable agriculture methods. However, the broad deployment of nano-pesticides is contingent upon resolving critical obstacles relating to environmental destiny, possible bioaccumulation, toxicity, and regulatory approval. The high expense of nanoparticle production and the necessity for uniform safety assessments further impede their commercialization, particularly for smallholder farmers in poor nations. Future study must focus on the long-term ecological impact of nano-pesticides, the development of biodegradable and biocompatible formulations, and their integration with precision agriculture and biological control tactics. Additionally, joint efforts between researchers, politicians, and industry stakeholders will be vital in building rigorous regulatory frameworks that assure the safe and responsible use of nano-pesticides. As scientific developments resolve existing uncertainties, nano-pesticides have the potential to play a crucial role in ensuring global food security while lowering the environmental footprint of conventional pesticide use.

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