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Original Article

Nano particles mediated delivery systems in insect pest management

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ABSTRACT

Crop protection against insects and diseases is highly dependent on the effective use of pesticides in agriculture. Even though they are extensively applied, traditional delivery systems are associated with shortcomings such as reduced efficiency, potential toxicity and adverse environmental effectiveness. Nano enabled smart delivery systems developed through nanotechnology offers solutions for targeted delivery of pesticides as well as environmental stability and controlled release of active ingredient. These delivery systems use nanoparticles which acts as carriers that can absorb, encapsulate and bind to pesticide molecules. Nano carriers such as liposomes, dendrimers, nano emulsions, nano capsules, solid-lipid nano particles, nanospheres, nanosuspensions, nanometals, nano micelles ensure efficient and prolonged availability of pesticide on crop and thus enhance their effectiveness against pest. Nevertheless, certain limitations still exist. This review explores the transformative impact of nano technology-driven inputs, particularly nano pesticides in modern agriculture. By integrating cutting-edge developments with sustainability goals, these nano-based innovations emerge as key contributors to enhance food production and long-term agriculture resilience.

Keywords: controlled release, nano-particles, pesticides, sustainable agriculture, targeted delivery

INTRODUCTION

The demand for efficient and sustainable crop protection strategies has become increasingly important across the globe. As the world population projected to hit 9.7 billion by 2050, agricultural productivity must rise by 50-70 per cent to ensure food security (FAO, 2017). Despite advancement in agricultural practices, biotic stresses, including pests, pathogens and weeds remain as major challenges in agriculture with arthropod pest accounts for 18-20 per cent reduction in yearly crop production resulting in economic losses more than US $ 470 billion annually, weeds for about 34 per cent of agricultural losses and on a regional and national scale, significant reduction in cop yields ranging from 20-40 per cent is reported due to pest and diseases. (Gharde et al. 2018; Oerke, 2006; Sharma et al. 2017). In modern agriculture, pesticides are indispensable for controlling biotic stress and sustaining national food security. But the main problem with traditional pesticides is that about 90 per cent of applied pesticides are lost due to spray drift, soil leaching, photolysis, hydrolysis and microbial degradation (Sabarwal et al. 2018). Merely about 1 per cent of pesticides reaches the target site and thus necessitating repeated application which causes economic losses as well as ecosystem pollution. Synthetic pesticides have long been the primary tools for mitigating biotic stress in agriculture, increasing resistance in target organisms coupled with adverse effect on non-target species and the environment hence the search for safer and more precise control measures becomes necessary (Damalas and Eleftherohorinos, 2011). Nano technology explores as a solution to these drawbacks of traditional pesticides. The integration of nano technology into pesticide formulation has emerged as a promising approach to enhance pesticide efficiency and safety compared to conventional formulation (Abdollahdokht et al. 2022). Nano pesticides offer a promising strategy to improve solubility, dispersion, bioavailability and protect active ingredients from early degradation and achieve controlled release triggered by environmental factors such as pH, light, humidity and temperature (Anandhi et al. 2020).

Nano pesticides

Nano pesticides are pesticide formulation in which active chemical compounds are incorporated into nano scale materials or nano particles which are engineered to exhibit unique physiochemical and biological properties (Abdollahdokht et al. 2022). Next- generation nano pesticides contribute to crop protection in two principal ways, either they can act as protective substances or by serving as nano scale delivery system for conventional pesticides (Mondejar-Lopez et al. 2024).

Nano particles:

Nano particles are the core building blocks of nano-technology, which are materials characterized by dimensions in the nano-scale range, typically less below 100 nm. Nanoparticles exhibit distinctive physicochemical and biological characteristics that arise primarily from their nanoscale dimensions and high surface-area-to-volume ratios. These properties may include enhanced mechanical strength, increased chemical reactivity, and improved electrical conductivity compared with their bulk counterparts (Bhattacharyya et al. 2010). Their unique behavior is governed by size-dependent quantum effects, surface chemistry, and atomic-scale structural arrangements, which collectively influence their physical, chemical, and biological functionalities (Leiderer and Dekorsy, 2008).

Physiochemical attributes of nano-particles influencing nano-pesticides performance in pest management:

Nano pesticides benefit from the inherent properties of nano particles, including nano scale dimension, large surface area, target specificity, crystallinity, permeability and heat stability which improve the efficiency of nano pesticides by better targeting, controlled release and greater environmental stability (Perlatti et al. 2013; Kah, 2015). Because of their extremely small dimensions, nano particles can easily infiltrate plant tissue and that are otherwise impermeable to larger delivery agents. Additionally, due to their high surface area to volume ratio, nano particles can be functionalized with specific ligands and accommodate significant payloads within their compact structure. While biodegradable nano particles break down over time, ensuring controlled release, non-biodegradable systems support sustained delivery. Modification on surface charge and chemistry further improve targeting efficiency and plant uptake (Rathore et al. 2024). The insect cuticle contains a diverse array of lipids that function to minimize water loss and prevent desiccation. Nano particles, upon contact, are absorbed into cuticular lipids and cause abrasion, ultimately causing insect death (Barik et al. 2008). Nano structuring pesticide molecules provide an effective strategy to regulate their residual impacts and nano delivery technologies improve the ability of these formulations to navigate environmental and biological barriers, resulting in efficient target-specific action (Balaure et al. 2017).

Common types of nano particles:

1. **Polymer based nano particles:** In these systems, active ingredients are enveloped within polymers sourced from natural and biodegradable materials, making them cost efficient. These polymers as amphiphilic in nature, i.e. having both hydrophilic and hydrophobic ends, which enables controlled release of pesticide molecules (Anandhi et al. 2020).
2. **Nano capsules:** Through nano encapsulation, pesticide active ingredients are enclosed within nano materials, allowing controlled release through mechanism including dissolution, diffusion, biodegradation and osmotic responses influenced by pH levels (Mondejar Lopez et al. 2024).
3. **Nano emulsions:** Nano emulsions are fine oil-in-water dispersions (5-200 nm in size) which are particularly useful for improving the application of hydrophobic pesticides that lack water solubility (Mustafa and Hussein 2020).
4. **Dendrimers:** Dendrimers are tree-like nano structures consisting of systematically arranged, customizable molecular building blocks, enabling accurate loading and delivery of active compounds (Rathore et al. 2024).
5. **Liposomes:** these are spherical structures composed of lipid bilayer nano scale vesicles which are designed to fuse with plant cell membrane to deliver active ingredient directly inside the cell (Rathore et al. 2024).
6. **Carbon nano tubes:** hollow tube-like nano structures that are capable of systemic delivery of active ingredients in plants (Rathore et al. 2024).

Nano particles as smart delivery systems

1. **Act as active ingredient**

   Nano pesticide formulations comprising zinc oxide nano particles, copper nano particles, silver nano particles and silicon nano particles offer broad spectrum activity and improved environmental safety compared to traditional formulations. Zinc, being an essential micronutrient, promotes plant growth while also acts as a toxicant to insect pests whereas silver nano particles possess extensive biological activity including antimicrobial, antifungal and pesticidal properties (Shahid et al. 2021). For example, (Debnath et al. 2011) reported that silica nano particles achieved complete (100 per cent mortality in adults of *Sitophilus oryzae* (rice weevil).

2. **Enhanced toxicity**

   Nano formulations of conventional insecticides can significantly increase their toxicity against target insect pest up to 10-folds. The nano encapsulated chlorantraniliprole and thiocyclam exhibited 3.86 and 2.06 times greater effectiveness, respectively against the black cutworm (*Agrotis ipsilon*) as compared to conventional pesticides (Manna et al. 2023).

3. **Enhanced solubility and uptake efficiency**

   This phenomenon involves a marked increase in the solubility of pesticides that usually exhibit limited solubility in aqueous or organic solvents. Moreover, converting these bulk compounds into nano-pesticides can increase their efficacy. Owing to their high surface area, nano insecticides exhibit stronger interactions with target pest ensuring effective action at lower doses (Manna et al. 2023).

4. **Targeted delivery and controlled release**

   Advanced nano pesticides delivery platforms, known as "stimuli-responsive nano insecticides" are designed to limit the overuse of active ingredients. In such systems AIs are released only when triggered by pest presence, with factors such as pH, temperature, light and specific enzymes acting as stimuli (Manna et al. 2023). Controlled release formulation of etofenprox, utilizing nano scale chitosan as a delivery carrier to regulate active ingredient release have proven effective in managing *Spodoptera litura* populations (Singh et al. 2024). Metal organic framework in contrast, enable efficient pesticide loading and controlled gradual release due to their highly ordered porous structure. As a result, numerous nano pesticides systems have shown enhanced efficacy over traditional commercially available formulations (Wang et al. 2023).

5. **Environmental stability**

   The majority of active ingredients used in insect pest management are prone to degradation under environmental stresses like UV exposure, oxidation and leaching etc. by incorporating these compounds into nano carriers, their durability can be enhanced, allowing them to remain effective for longer period and make them more stable (Manna et al. 2023).

Pest control mechanism

The mesoporous nature of nano pesticides enables the formation of tiny surface traps on plants, thereby increasing pesticide retention and promoting stronger interaction with pests. The mode of active ingredient release, governed by the surface properties of nano carriers, support targeted interaction with pest physiology, amplifying their lethal impact. Moreover, their nano scale size further enables easy penetration through plant tissues, including roots and epidermis, enhancing systemic distribution and pest control efficiency (Abd El-Azeim et al. 2020). Certain nano pesticides are engineered to deliver active ingredients directly to pest affected sites using targeted delivery systems, thereby improving efficacy and reducing the impact on non-target species. The intrinsic features of nano materials support the creation of advanced controlled- release pesticide system. Their sensitivity to environmental cues like humidity, temperature and Ph enables on-demand and regulated release of active ingredient (Tang et al. 2023).

Advantages:

1. Compared to conventional pesticides, nano pesticides offer more eco-friendly alternative due to their reduced non-specific effects on beneficial insects and microbes which contributes to improved crop protection. Their nano scale nature reduces unintended impacts on beneficial organisms, leading to targeted pest management and lower the risk of contamination of soil and aquatic systems (Tang et al. 2023).
2. With nano encapsulation, pesticides can achieve controlled release kinetics, better permeability and enhanced stability and solubility. They extend the lifespan of pesticides and safeguard active ingredient from degradation under adverse conditions and thereby enhancing pest control outcomes (Kah and Hofmann 2014).
3. When applied judiciously, nano pesticides have the potential to improve crop productivity, enhance food safety and increase nutritional quality (Wang et al. 2020).
4. With improved penetration, superior absorption, nano-based formulations achieve similar efficacy to traditional pesticides while using at much lower doses, thereby lowering environmental contamination (Nair et al. 2010).

Limitations

1. Since nano pesticides possess strong pesticidal properties, they can pose toxicity risk to non-target organisms. The extent of these adverse effects depends on factors such as nano pesticide characteristics, species sensitivity, exposure pathways, concentration levels and environmental conditions (Wang et al. 2022).
2. Run off from agricultural fields and industrial wastewater can carry nano pesticides into soil where they migrate through leaching, eventually reaching water resources, affecting quality and increasing risks to both humans and ecosystems (Chaud et al. 2021).
3. Owing their small size, nano formulations often aggregate into cluster or even destabilized the matrix, thereby modifying their surface properties which results in loss of their nano-specific behavior, opposing the fundamental intent behind their creation (De Oliveira et al. 2020).
4. Some other limitations are the expensive production cost in nano material development and the relatively low economic return from agriculture (De Oliveira et al. 2020).

CONCLUSION

Nano particles mediated delivery systems represents a transformative advancement in insect pest management by integrating principles of nano technology with crop protection science. The unique physiochemical properties of nano particles, facilitate improved loading, protection and targeted delivery of active ingredients. These systems enable controlled release, including stimuli-responsive mechanism triggered by environmental cues and thereby maximize pesticidal efficiency while minimizing non-target exposure and environmental losses. Despite these promising attributes, the deployment of nano-pesticides necessitates critical evaluation of their environmental fate, transformation and ecotoxicological impacts. Additionally, economic constraint associated with large-scale production remain a barrier to widespread adoption. Therefore, future research should emphasize the design of biocompatible, biodegradable and cost-effective nano formulations supported by advanced characterization techniques and field-scale validation which should be efficient and sustainable for modern agriculture.

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