REVOLUTION OF NANOPESTICIDES IN INSECT PEST MANAGEMENT: A COMPREHENSIVE REVIEW

Irfan Ahmed Noorani*, Baqia Farhat, Ibraq Khurshid, Zeeshan Yasin
Department of Zoology, Central University of Kashmir, Ganderbal, J&K, India-191201
**Corresponding author email: irfan.noorani29@gmail.com*

KEYWORDS
Nanoparticle
Nanopesticide
Pest control
Agriculture
Public Health

ABSTRACT
Pest management is essential to agriculture and public health, and sustainable solutions must be deployed to control the risks associated with pests. Traditional methodologies are limited because of pesticide resistance and other hazardous environmental ramifications. Currently, nanoparticles are one promising aspect with potential applications in pest control. This review discusses nanoparticle use in pest management in agriculture and the public arena. Metallic nanoparticles utilize cell disruption, while polymeric nanoparticles interfere with reproduction and development, and lipid nanoparticles deliver pesticides that are on target. Nanoparticle synthesis involves various physical, chemical, and biological methods, including several delivery mechanisms such as sprays, coatings, encapsulation, oral feeding, nanocarriers, and hydrogels. Consequently, providers enable the effective deployment of nanoparticles, which effectively impacts pest control. Moreover, besides increasing crop yield and quality in agriculture, nanoparticles are promising in controlling disease vectors, which also take part in public health advantages. However, toxicity, environmental impact, and regulation considerations should be analyzed to ensure safe nanoparticle use and sustainability. Future research directions encompass precision agriculture, disease management, environmental impact assessment, regulatory compliance, and the development of safe and effective nanoparticle-based pest management products. Therefore, all stakeholders must work together to overcome these obstacles and fully utilize nanoparticle-based pest control to benefit public health and agriculture.

1. Introduction

Pest management contributes as a vital component in both agriculture and public health. Agriculture ensures that crop production is not compromised and economic loss is minimized from pest attacks. Integrated Pest Management (IPM) is a sustainable approach that includes several control methods, including but not limited to biological, cultural, physical, and chemical control measures. It helps maintain the insect population and sub-economic levels. This method manages the financial risks and eliminates the excessive impact arising from the use of pesticides on humans and the environment, according to the study by Dey et al. (2021). Furthermore, ecological pest management methods must be applied in urban agriculture for environmental and public health (Arnold et al., 2019). One significant sub-discipline of pest management has been identified as habitat management's suppression of pest populations (Gurr et al., 2017). Because pests act as disease reservoirs, pest control is crucial for enhancing food security and in the context of public health. For example, improving public health and food security requires controlling rodent populations, which are significant agricultural pests and disease reservoirs (Donga et al., 2022). Furthermore, agriculture directly benefits from natural pest management's role as an ecosystem service, which also helps with pollination and pest control (Parry & Schellhorn, 2013). Contest management methods invariably have unanticipated consequences on the environment, public health, and surrounding farm production (Waterfield & Zilberman, 2012). One of the drawbacks of the use of contemporary methods of pest control in agriculture is the emergence of resistance to these methods in insects brought about by the unchecked use of chemical pesticides. In addition, chemical pesticide use harms animals, humans, and the environment (A S & Thangapandiyan, 2019).

Additionally, conventional approaches to integrated pest management (IPM) must be improved, (Riyaz et al., 2022). Furthermore, traditional methods for identifying pests, such as the manual monitoring of agricultural specialists, are labour-intensive, subjective, and might need to be more scalable, (Dong et al., 2022). These difficulties have prompted researchers to investigate cutting-edge methods of controlling pests, like the application of nanotechnology. Nanoparticles are defined as those particles that have at least one of their dimension less than 100nm. Nanoparticles have found wide-ranging applications, including but not limited to health, material sciences and agriculture. Due to their unique structural properties, such as high surface area to volume ratio, inimitable chemical and physical characteristics, and potential to act as delivery agents, Nanoparticles have wide-ranging applications (Strambeanu et al., 2014). Several preliminary studies suggest that nanoparticles offer a beneficial alternative to conventional methods of pest control (Kumar et al., 2021; Wang et al., 2019).

The novelty of nanoparticles as a pest management tool shall address some of the drawbacks associated with the conventional approaches. Though Integrated Pest Management (IPM) has been a primary focus of sustainable pest management techniques over the past few decades, it still uses synthetic insecticides to some extent. Riyaz et al. (2022) revealed that incorporating nanoparticles in the IPM regimens can reduce and overcome the use of these harmful chemicals. Pesticide resistance against several chemical pesticides has been of growing concern. As such, this adds further impetus to exploring the use of nanoparticles in pest management to address this detrimental limitation of synthetic pesticides in everyday use (Wang et al., 2019). Nanoparticles also have unique properties, such as the power to penetrate the insect cuticle, allowing them to bypass the defence mechanism of several insect pests (A S & Thangapandiyan, 2019); (Xu et al., 2020). Nanoparticles being versatile in their composition with formulation ranging through a wide array of bioactive components and metals have been implicated in insecticidal activity against a variety of pests, as reported by Wang et al. (2019). Nanotechnology, as an emergent field of the 21st century, is being used in a variety of ways to target pests, notably through the construction of nanostructured materials which show insecticidal action, such as alumina and zinc oxide nanoparticles (Pittarate et al., 2021; Stadler et al., 2010). In their study, Yan et al. (2020) exhibited that the nanoparticles have mitigated the shortcomings of traditional methods of dsRNA delivery and thereby have shown improved outcomes in pest management mediated by RNA interference (RNAi). The use of entomopathogenic fungi-based nanoparticles to target insect pests is another facet where nanotechnology has been employed to develop exceptional techniques of pest control (Wang et al., 2021; Wu et al., 2021). Similarly, nano-formulations of insect pathogens have shown promising outcomes in a study conducted by Xu et al. (2020) examining the effect of these nano-formulations against insect pests. It is pertinent to mention that using nanoparticles as an alternative pest management strategy has challenges and limitations. Due to the developing technique, possible environmental implications and unexpected consequences arising from nanoparticle pest management strategy need further study and critical analysis (Zayed, 2020). The other dimension of challenges, as elucidated by Zhao et al. (2022), is the scalability and practical implication of these approaches.

2. Nanoparticles Used in Agricultural Pest Control

The evolution of nanoparticles is regarded as the most recent discovery in crop protection. Several nanoparticles, like metal nanoparticles, metal oxide nanoparticles and polymer-based nanoparticles, have been developed for pest management (Ragaei and Sabry 2014). Based on composition, nanoparticles employed in pest control may be divided into two broader groups: Organic and Inorganic (figure 1). Concerning pest control, every kind of nanoparticle has certain qualities and benefits.

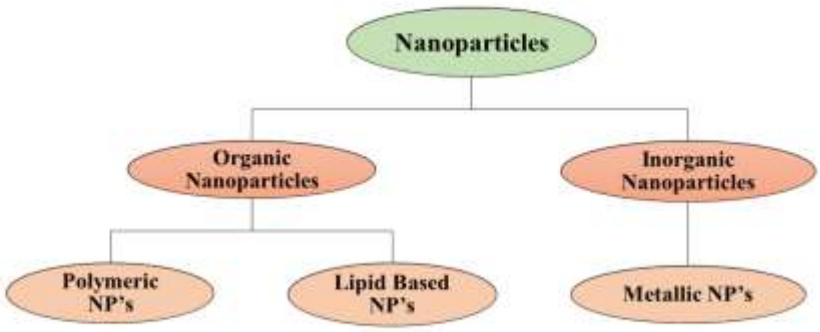

Figure 1: Types of nanoparticles.

2.1 Metallic: Metallic nanoparticles, including silver and gold, have demonstrated significant insecticidal activity against various pests. Due to their large surface area to volume ratio, these nanoparticles interact more effectively with insect cuticles, enhancing their efficacy as pest control agents. They exhibit broad-spectrum impact against numerous insect species and hold the potential to replace conventional chemical pesticides. Furthermore, metallic nanoparticles show promise in overcoming insect pesticide resistance, making them valuable tools in integrated pest management systems (Gong et al., 2013; Sahayaraj et al., 2016).

2.2 Zeolite: These are aluminosilicates with crystalline structures and unique nanoporous channels, making them suitable for various agricultural applications. Zeolite nanoparticles have been utilized as carriers for pesticides and other antimicrobial compounds. They facilitate the slow and controlled release of the adsorbed active agents within their porous structure, thereby enhancing the sustainability and efficacy of pesticide use in agriculture (Smedt et al., 2015).

2.3 Polymeric: Polymeric nanoparticles, as the name suggests, are synthesized by the polymerization process and include the likes of chitosan and biochar. Polymeric nanoparticles have reduced environmental impacts owing to their biodegradable nature and, therefore, have the potential to be integrated into sustainable agriculture practices. These have been explored for their insecticidal and pest control properties and offer certain advantages such as prolonged efficacy and controlled release of active compounds. Polymeric nanoparticles have also been utilized as a platform or carrier for encapsulating and delivering pesticides and other bioactive agents. Pesticides delivered through polymeric nanoparticles have increased stability in the environment and therefore enhanced bioavailability (Wang et al., 2021; Wu et al., 2021; Oliveira et al., 2018).

2.4 Lipid-Based: These include nanoparticles such as nanoencapsulated essential oils. Lipid-based nanoparticles have shown pesticidal properties in various agricultural settings. These nanoparticles act through fumigant activity and odour action and are utilized off-field in storage facilities. Therefore, they are a safe and eco-friendly alternative to synthetic chemical pesticides and can be used in sustainable agricultural pest management (Christofoli et al., 2015; Sabbour, 2020).

3. Synthesis of Nanoparticles

Synthesis of nanoparticles involves various methods, which can be clubbed into three principle classes: i) physical, ii) chemical and iii) biological methods. The first class of these, i.e., the physical methods, are based on processes such as nucleation and growth. These include techniques such as lithography, laser ablation, and vapour condensation (Henglein, 1993). The second class, i.e., chemical method of nanoparticle synthesis, involves chemical reactions in solution or at interfaces. Chemical methods include techniques such as reduction and precipitation (Murray et al., 2000). Both offer precise control over nanoparticle form, size, and composition, essential for their specific applications (Alivisatos, 1996).

On the other hand, biological synthesis, often called "green synthesis," uses biotic components to synthesize nanoparticles. Various plants, algae, bacteria, fungi, and other biologicals are used in the green synthesis. As the name suggests, green synthesis is an environmentally friendly and sustainable method that uses capping and reducing agents found in biological systems to speed up the production of nanoparticles (Iravani, 2011). This method has added benefits, including the possibility of large-scale manufacturing, sustainability, gentle reaction conditions, and biocompatibility for medical use (Singh et al., 2015).

Another classification of nanoparticle synthesis techniques is based on the approach used to attain the requisite size. Based on this, classification techniques can be either top-down or bottom-up approaches. In the top-down approach, by processes such as etching, grinding, and milling, more extensive bulk materials are reduced to nanoparticle size (Sun et al., 2002). This method is associated with high energy consumption and limited scalability, though it offers precise control over the shape and size of nanoparticles (Chen et al., 1999). Alternatively, the bottom-up approach involves building nanoparticles from atomic or molecular precursors using chemical vapour deposition, self-assembly, and molecular beam epitaxy. Bottom-up synthesis offers advantages such as atomically precise control, scalability, and the ability to engineer complex nanostructures with tailored functionalities (Alivisatos, 1996).

4. Nanopesticides Bioassay

Before applying nanopesticides in various crop pest management they can be tested against a particular pest to evaluate their efficacy (figure 2). Nanpesticides are synthesized by combining different nanomaterials such ZnO, Ag_2O, Al_2O and active insecticidal compounds (Kamaraj et al., 2012). The toxicity of nanoparticles can be evaluated through the minimum inhibitory concentration that employs the agar well diffusion method. Nanopesticides are usually coated over the outer surface of filter paper and are directly applied to the target pest for oral feeding (Lade & Patil, 2017).

The pupicidal activity of nanopesticides is important for preventing the attack by pupae of different pests. The pupicidal activity can be measured by applying nanopesticides to the pupae of target pests. The mortality rate is measured after one day which also depends upon the concentration of nanopesticides. Sivapriyajothi et al. (2014) observed that nanoparticles synthesized from the extract of *Leucas aspera* show pupicidal activity against larvae of mosquito vectors.

Similarly, the larvicidal activity of the nanopesticides can be measured through the leaf disc method. The nanopesticides are introduced into the leaf, and the concentration of larvae can be determined after 96 hours. Some plants, like the leaf extract of *Ambrosia arborescens*, show larvicidal activity against some pests (Morejon et al., 2018).

Further, the anti-feeding activity of nanopesticides can be measured through their application to leaf discs of pest food. The one-third instar larva is introduced to the leaf, and the damage caused by leaf-eating can be measured after 24 hours. In *Helicoverpa armigera*, anti-feeding activity was observed by applying silver nanopesticides. (Siva & Kumar, 2015).

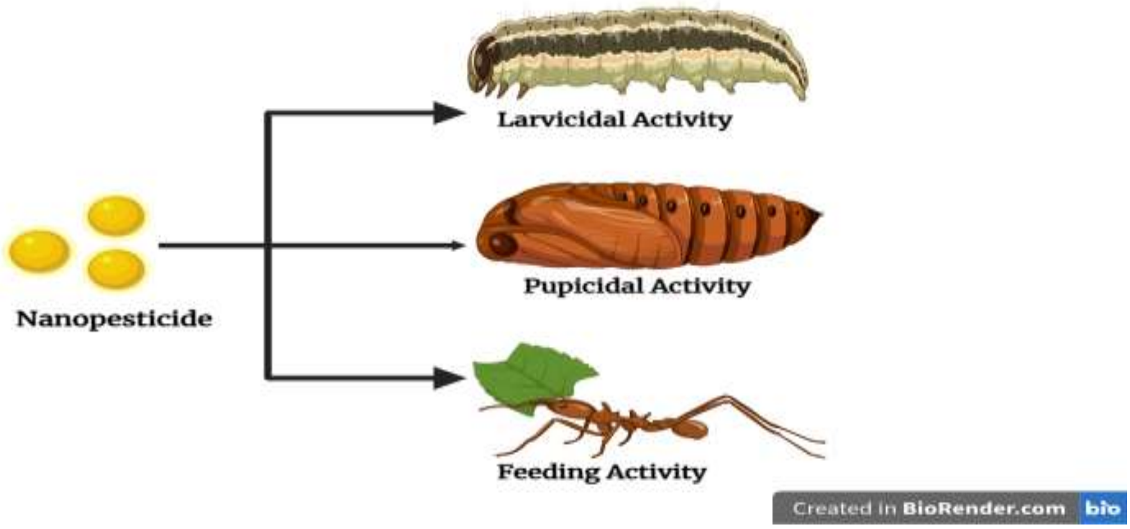

Figure 2. Nanopesticide efficacy

5. Insecticidal Mechanism of Nanoparticles

Benelli et al. (2017) highlight that recent studies have significantly advanced our understanding of how to formulate nanoparticles with active toxic compounds and how these nanoparticles interact with insect pests. These interactions involve diverse mechanisms at cellular and subcellular levels, including disruption of cellular processes, interference with reproductive mechanisms, targeted delivery of pesticides, etc. (figure 3).

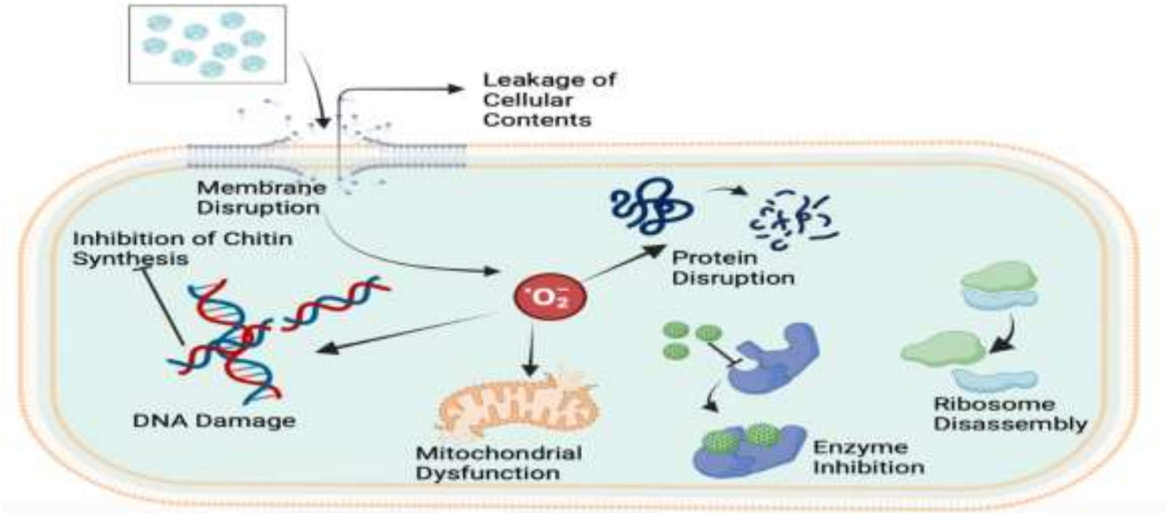

Figure 3: Insecticidal Mechanism of Nanoparticle

5.1 Disruption of Cellular Processes: It has been exhibited that nanoparticles disrupt essential cellular processes that can interfere with vital metabolic pathways, cellular signalling, or structural integrity, which leads to adverse physiological and biochemical imbalances, ultimately contributing to mortality or reduced fitness in the target pests. (Benelli, 2018).

5.2 Targeted Delivery of Pesticides: Nanoparticles can be used to deliver pesticides and other active compounds to target species with a very narrow spectrum, which has been elucidated by Yan et al. (2020) in their study where they have shown that nanoparticles can be effectively used to deliver pesticides and dsRNA while simultaneously allowing precise and regulated release of these ingredients that improve stability and bioavailability for efficient pest control. Therefore, it also has the added benefit of preventing ecosystem disruptions and environmental damage.

5.3 Insecticidal Effects: Gutiérrez-Ramírez et al. (2021) report that a few nanoparticles, like that of zinc oxide and titanium dioxide, have been implicated in having insecticidal effects on pest populations. This method has, moreover, not been reported to be prone to the development of resistance in insect pests. Therefore, the desiccation-attributed mode of action of the nanoparticles reinforces their usage.

6. Delivery Methods Employed:

When broadly classified, the use of nanoparticles in pest management can be divided into two categories. In one category, the nanoparticles themselves are used as pest control agents. In contrast, in the other, the nanoparticles act as delivery systems that carry a load of pesticides or other toxic compounds that can be targeted to specific plant parts (Worrall et al., 2018). In either of these cases, nanoparticles are delivered to the target site using various delivery methods, including sprays, coatings, encapsulation, oral feeding, smart nanocarriers, and hydrogels (figure 4).

Figure 4: Delivery methods of nanoparticles.

6.1 Spray-based: Spray-based delivery systems involve the direct application of suspensions or solutions of nanoparticles to target sites. This method ensures uniformity in application and distribution while facilitating efficient contact with the pests and their environments (Cagliari et al., 2019).

6.2 Coating-based: In this method of nanoparticle application in agricultural settings, seeds, fruits, or other structures and surfaces are coated with nanoparticles. Coatings provide long-term protection against pests by slow and controlled release of active compounds over time (Yan et al., 2020).

6.3 Encapsulation-based: Sensitive bioactive substances are protected and delivered in nano-encapsulating platforms. This method ensures that the bioactive compounds retain their activity over a long period and helps in precise targeting and controlled release of such substances, improving the efficacy of pest control. Encapsulation also minimizes off-target effects and ecological impacts by delivering the pesticides directly to the pests (Raliya et al., 2017).

6.4 Oral feeding-based: This method involves nanoparticles with the systemic mode of action, designed so that the pests take them up through the oral route and have been employed to deliver dsRNA and bioactive substances. This method enables precise delivery, facilitating efficient gene silencing and RNA interference (RNAi) (Yan et al., 2020).

6.5 Smart nanocarrier-based: This method is similar to nanomedicine in humans, where nanoparticles are tailored to fulfil desired requirements precisely, controlled and efficiently. Smart nanocarriers enhance active compounds' stability and delivery efficiency, offering innovative and environmentally friendly pest control solutions (Li et al., 2023).

6.6 Hydrogel-based: In this delivery system, hydrogel matrices are used. Hydrogel matrices loaded with bioactive compounds ensure the prolonged and controlled release of the cargo, providing an effective and long-lasting approach to pest management and are particularly useful in precision agriculture and controlled release applications (Yang et al., 2022).

7. Applications in Agricultural Pest Control

Recently, there has been increased interest in exploring nanotech alternatives to conventional crop protection methods. So far, research has predominantly focused on the effect of nanoparticles on crop quality, production, and insect resistance while also considering the safety, efficacy and environmental sustainability associated with their use. Promising results were obtained, where the researcher demonstrated the insecticidal activity of some nanoparticles, particularly that of titanium dioxide and zinc oxide nanoparticles (Gutiérrez-Ramírez et al., 2021). Nanoparticles have also been used to treat plant diseases, acting either directly or indirectly, where the former involves the direct application of nanoparticles to reduce and eliminate disease-causing agents. The latter uses nanoparticles as carriers for pesticides and bioactive compounds in everyday use to enhance their efficacy and narrow their spectrum (Worrall et al., 2018). Consequently, applying nanoparticles can have secondary benefits besides controlling pests and diseases. Notable among these secondary benefits is the increased agricultural productivity, as demonstrated in a study conducted by Yasir Wasaya et al. (2020) on foliar application of nanoparticles on mungbean, which enhanced crop growth and yield characteristics.

Numerous nanoparticles have been tested for their activity and efficiency against various insect pests that substantially threaten agricultural output and food security. Rai and Ingle (2012) investigated the efficiency of silver nanoparticles against *Tuta absoluta* (tomato leafminer) infestations in tomato crops. Copper nanoparticles show promise for targeting *Diabrotica virgifera* (Western corn rootworm) in maize fields (Wu et al., 2019). Ndakidemi et al. (2016) investigated using titanium dioxide nanoparticles to suppress *Plutella xylostella* (diamondback moth) in cruciferous crops. Iron oxide nanoparticles were analyzed for their effectiveness against *Rhopalosiphum padi* (bird cherry-oat aphid) in wheat fields (Chattopadhyay et al., 2017). Chitosan nanoparticles were considered for regulating *Helicoverpa armigera* (cotton bollworm) in cotton crops (Ramanujam, et al., 2014).

In addition, Noda et al. (2008) investigated using gold nanoparticles to target *Frankliniella occidentalis* (Western flower thrips) in greenhouse crops. Zinc oxide nanoparticles were tested for their efficiency against *Sitophilus oryzae* (rice weevil) infestations in stored grains (Rodrigues & Figueira, 2016). Hazafa et al. (2022) studied the use of silica nanoparticles to target *Myzus persicae* (green peach aphid) in potato crops. Cerium oxide nanoparticles have been investigated for managing *Leptinotarsa decemlineata* (Colorado potato beetle) in potato crops (A S & Thangapandiyan, 2019).

Deka et al. (2021) also investigated polymeric nanoparticles loaded with neem oil for controlling *Spodoptera exigua* (beetroot armyworm) in vegetable gardens. Silver-copper hybrid nanoparticles have been studied to attack *Aphis gossypii* (cotton aphid) in cotton farms (Shahid et al., 2021). Magnetic nanoparticles to control *Tribolium castaneum* (red flour beetle) in stored grain facilities were analyzed by Kumar, et al. (2021). Lipid nanoparticles containing garlic extract have been studied to regulate *Rhyzopertha dominica* (the lesser grain borer) in grain storage systems (Santos, et al., 2021). This research highlights the promise of nanoparticle-based techniques as targeted and efficient pest management tactics in agriculture, opening the door for more sustainable crop protection practices.

8. Challenges and Limitations

Although applying nanotechnology in pest management is beneficial in some aspects, it also has certain constraints. These limitations include, notably, toxicity and environmental concerns, as well as regulatory issues. Research carried out through several studies has tried to overcome these limits; nonetheless, several lacunae in our current knowledge still require additional investigation to understand fully.

8.1 Environmental Impacts: Nanoparticles, owing to their inherent properties, such as permanence and mobility, have the potential to accumulate in the environment. It has sparked a worry about the environmental implications of nanoparticles, suggesting that though nanoparticles have advantages, environmental concerns should not overshadow any possible benefits. Fadiji et al. (2022) emphasize the need to ensure proper investigation of the ecological impact of nanoparticles so that long-term and safe use of nanoparticles in crop protection can be assured. Similarly, Zayed (2020) emphasize the need to monitor and understand the post-application behaviour of nanoparticles in the environment to avoid any negative repercussions arising from their widespread use. Further, Laizer et al. (2019) suggest rigorous investigation and risk evaluation to prevent unforeseen ecological disruptions due to off-target impacts.

8.2 Toxicity Concerns: Without rigorous in-vitro lab testing, it would not be suitable to say that nanoparticles are non-toxic to the vast array of biodiversity in the environment. Yan et al. (2020) point out in their study that this issue must be addressed to mitigate adverse impacts on biodiversity and the ecosystem. Therefore, to ensure the safe and long-term use of nanoparticle-based pest management strategies, the potential toxicity of nanoparticles to non-target species and beneficial organisms must be evaluated (Rai & Ingle, 2012).

8.3 Regulatory Considerations: Nanotechnology, an emergent scientific field, needs proper surveillance and regulatory guidelines to prevent misuse. Unless the gap in knowledge about the potential side-effects of using nanoparticles in pest management is substantially filled up with new studies, the use of nanoparticles in the environment should be restricted without impacting its development. It requires coordinated efforts among various stakeholders, including scientists, policymakers, and industry stakeholders, who need to work in tandem to address the legal and financial challenges associated with nanoparticle-based biopesticides programme implementation (Bouma, 2019).

9. Future Perspectives

To increase efficacy and sustainability in nanoparticle-based pest management practices shows excellent optimism. Ongoing research and possible future advancements in nanoparticle-based pest control have significant opportunities for improving effectiveness and sustainability. Additional research is required to address numerous critical areas and obstacles to realize the potential of nanoparticle-based pest control solutions fully. Some of the focus areas are mentioned herein:

9.1 Precision Agriculture: Precision agriculture research has recently gained prominence and can be strengthened by synergistic tailoring of nanoparticle formulations to tackle crop variability within and across fields. Research should focus on the development of nanoparticle formulations which can deliver an exact and continuous release of agrochemicals to obtain optimal plant dosage, boosting crop production and minimizing environmental effects (Duhan et al.,2017; Raliya et al., 2017)

9.2 Plant Disease Management: Nanoparticles have been shown to possess inherent antimicrobial properties against a wide array of disease-causing microbes. Understanding the mechanisms and effects of nanoparticles in treating bacterial and fungal infections in agricultural settings is essential for developing sustainable and effective pest control methods. It is the need of the hour to focus our research on building nano-encapsulating insecticides in matrices offering regulated release and nanocarriers for topical RNA interference approaches to improve crop protection (Hamid & Saleem, 2022; Li et al., 2022).

9.3 Ecological impact and safety assessment: The conventional practices of pest management can only be substituted with the novel methods of nanoparticle-based pest management when it is scientifically established that there are none or at least minimal environmental and safety concerns associated with using nanoparticles in commercial settings. Therefore, another focus area of research should deal with assessing the safety and environmental implications of employing nanoparticles in agriculture, as it is critical to investigate nanoparticle ecotoxicity and potential impact on the environment or public health (El-Temsah & Joner, 2011)

9.4 Safe and Effective Products: The farmer's adoption of nanoparticle-based pest management products depends on the efficacy and effectiveness of these products in dealing with pests compared with conventional methods. Therefore, we must focus our research on developing practical solutions that primarily deal with pest infestations and enhance crop yield. In this domain, research must focus on green synthesized nanoparticles shown by some previous studies to influence crop growth and production (Pardva, 2023; Saleem et al., 2021).

Conclusion

Nanotechnology has emerged as one of the most promising alternatives to conventional pest management practices worldwide. Several unique properties of nanoparticles, such as their high surface area to volume ratio and the ability to carry and deliver bioactive cargo precisely, can be leveraged to address many of the limitations of traditional methods. Several nanoparticles, such as metallic, polymeric, and lipid-based, have been employed in agricultural settings and have shown promising results in tackling the pest menace. Moreover, they work by diverse mechanisms ranging from cell membrane disruption to interfering with normal sub-cellular processes, accompanied by their targeted delivery, thereby enhancing efficacy while minimizing environmental impacts. However, some challenges are posed by applying nano-pesticides in agriculture, notably the knowledge gap on the toxicity and non-target effects of nanoparticles and the need for proper legislative policies to regulate their use. Comprehensive research is essential to eliminate these challenges and establish safety in these technologies' long-term use. Innovation and safety must be balanced by establishing fool proof and efficient regulatory frameworks formulated by cooperative collaboration between various stakeholders, such as researchers, policymakers, and industrialists. Improving disease management, precision agriculture and conducting thorough environmental impact assessments should be a focus of future research in this domain. Further, coordinated efforts to overcome these limitations are needed to develop safer, more effective nanoparticle-based pest management products and establish more sustainable pest management practices.

Declaration of Competing Interest

The authors declare that they have no conflict of interest that could have appeared to influence the work reported in this paper.

References

A S, A. and Thangapandiyan, S. 2019. Comparative bioassay of silver nanoparticles and malathion on infestation of red flour beetle, *Tribolium castaneum*. *The Journal of Basic and Applied Zoology*. **80**(1): https://doi.org/10.1186/s41936-019-0124-0

Alivisatos, A.P. 1996. Semiconductor clusters, nanocrystals, and quantum dots. *Science*. **271**:933-937. https://doi.org/10.1126/science.271.5251.933

Arnold, J., Egerer, M. and Daane, K.M. 2019. Local and landscape effects to biological controls in urban agriculture-A Review. *Insects*. **10**(7):215. https://doi.org/10.3390/insects10070215

Benelli, G. 2018. Mode of action of nanoparticles against Insects. *Environmental Science and Pollution Research*. **25** (13):12329-12341. https://doi.org/10.1007/s11356-018-1850-4

Benelli, G. and Lukehart, C.M. 2017. Special issue: Applications of green synthesized nanoparticles in pharmacology, parasitology and entomology. *J. Clust. Sci.* **28**(1):1–2. https://doi.org/10.1007/s10876-017-1165-5

Bouma, J. 2019. How to communicate soil expertise more effectively in the information age when aiming at the UN sustainable development goals. *Soil Use and Management.* **35**:3238. https://doi.org/10.1111/sum.12415

Cagliari, D., Dias, N.P., Galdeano, D.M., Dos Santos, E.Á., Smagghe, G. and Zotti, M.J. 2019. Management of pest insects and plant diseases by non-transformative RNAi. *Frontiers in Plant Science*. **10**: 1319. https://doi.org/10.3389/fpls.2019.01319

Chattopadhyay, P., Banerjee, G. and Mukherjee, S. 2017. Recent trends of modern bacterial insecticides for pest control practice in integrated crop management system. 3 *Biotech*, **7**(1):60. https://doi.org/10.1007/s13205-017-0717-6

Chen, S. and Kimura, K. 1999. Synthesis and characterization of carboxylate-modified gold nanoparticle powders dispersible in water. *Langmuir,* **15**(4): 1075-1082. https://doi.org/10.1021/la9812828

Christofoli, M., Costa, E.C.C., Bicalho, K.U., de Domingues, V.C., Peixoto, M.F., Alves, C.C.F., Araújo, W.L. and de Melo Cazal, M. 2015. Insecticidal effect of nanoencapsulated essential oils from *Zanthoxylum rhoifolium* (Rutaceae) in *Bemisia tabaci* populations. *Industrial Crops and Products*. **70**:301-308. https://doi.org/10.1016/j.indcrop.2015.03.025

de Oliveira, J.L., Campos, E.V.R., Pereira, A.E.S., Nunes, L.E.S., da Silva, C.C.L., Pasquoto, T., Lima, R., Smaniotto, G., Polanczyk, R.A. and Fraceto, L.F. 2018. Geraniol encapsulated in chitosan/gum arabic nanoparticles: a promising system for pest management in sustainable agriculture. *Journal of Agricultural and Food Chemistry*. **66**(21):5325-5334. https://doi.org/10.1021/acs.jafc.8b00331

Deka, B., Baruah, C. and Babu, A. 2021. Entomopathogenic microorganisms: their role in insect pest management. *Egyptian Journal of Biological Pest Control*. **31**(1). https://doi.org/10.1186/s41938-021-00466-7

Dey, U., Sarkar, S., Malik, M., Sehgal, M., Debbarma, P. and Chander, S. 2021. A promising sustainable pest management technology: microbial bio-control agent. *Microbiology Research Journal International*. **31**(12):12-30. https://doi.org/10.9734/mrji/2021/v31i1230361

Dong, S., Du, J., Jiao, L., Wang, F., Liu, K., Teng, Y. and Wang, R. 2022. Automatic crop pest detection oriented multiscale feature fusion approach. *Insects*. **13**(6):554. https://doi.org/10.3390/insects13060554

Donga, T.K., Bosma, L., Gawa, N. and Meheretu, Y. 2022. Rodents in agriculture and public health in malawi: farmers' knowledge, attitudes, and practices. *Frontiers in Agronomy*. 4:936908. https://doi.org/10.3389/fagro.2022.936908

Duhan, J.S., Kumar, R., Kumar, N., Kaur, P., Nehra, K. and Duhan, S. 2017. Nanotechnology: The new perspective in precision agriculture. *Biotechnology Reports*. 15:11-23.

https://doi.org/10.1016/j.btre.2017.03.002

El-Temsah, Y.S. and Joner, E.J. 2011. Impact of Fe and Ag nanoparticles on seed germination and differences in bioavailability during exposure in aqueous suspension and soil. *Environmental Toxicology*. **27**(1):42-49. https://doi.org/10.1002/tox.20610

Fadiji, A.E., Nhlanhla Mthiyane, D.M.N., Onwudiwe, D.C. and Babalola, O.O. 2022. Harnessing the known and unknown impact of nanotechnology on enhancing food security and reducing postharvest losses: constraints and future prospects. *Agronomy*. **22**(7):1657. https://doi.org/10.3390/agronomy12071657

Gong, L., Chen, Y., Hu, Z. and Hu, M. 2013. Testing insecticidal activity of novel chemically synthesized sirna against *Plutella xylostella* under laboratory and field conditions. *PloS One.* **8**(5):e62990. https://doi.org/10.1371/journal.pone.0062990

Gurr, G.M., Wratten, S.D., Landis, D.A. and You, M. 2017. Habitat management to suppress pest populations: progress and prospects. *Annual Review of Entomology*. **62**(1): 91-109. https://doi.org/10.1146/annurev-ento-031616-035050

Gutiérrez-Ramírez, J.A., Betancourt-Galindo, R., Aguirre-Uribe, L.A., Cerna-Chávez, E., Sandoval-Rangel, A., del Ángel, E.C., Chacón-Hernández, J.C., García-López, J.I. and Hernández-Juárez, A. 2021. Insecticidal effect of zinc oxide and titanium dioxide nanoparticles against *Bactericera cockerelli* Sulc. (Hemiptera: Triozidae) on tomato *Solanum lycopersicum*. *Agronomy*. **11**(8):1460. https://doi.org/10.3390/agronomy11081460

Hamid, A. and Saleem, S. 2022. Role of nanoparticles in management of plant pathogens and scope in plant transgenics for imparting disease resistance. *Plant Protection Science*. **58**(3): 173-184. https://doi.org/10.17221/37/2020-pps

Hazafa, A., Murad, M., Masood, M., Shahid, B., Khan, M., Farooq, Q., … and Naeem, M. 2022. Nano-biopesticides as an emerging technology for pest management. https://doi.org/10.5772/intechopen.101285

Henglein, A. 1993. Physicochemical properties of small metal particles in solution: “microelectrode” reactions, chemisorption, composite metal particles, and the atom-to-metal transition. *The Journal of Physical Chemistry*. **97**: 5457-5471.

Iravani, S. 2011. Green synthesis of metal nanoparticles using plants. *Green Chemistry*. **13**: 2638-2650.

Kamaraj C., Rajakumar G., Rahuman A.A., Velayutham K., Bagavan A. and Zahir A.A. 2012. Feeding deterrent activity of synthesized silver nanoparticles using *Manilkara zapota* leaf extract against the house fly, *Musca domestica* (Diptera: Muscidae). *Parasitology Research*. **111**(6):2439-2448.

Kumar, P., Pandhi, S., Mahato, D., Kamle, M. and Mishra, A. 2021. *Bacillus*-based nano-bioformulations for phytopathogens and insect–pest management. *Egyptian Journal of Biological Pest Control*. **31**(1):128. https://doi.org/10.1186/s41938-021-00475-6

Lade B.D. and Patil A.S. 2017. Silver nano fabrication using leaf disc of *Passiflora foetida* Linn. *Applied Nanoscience*. **7**(5):181-192.

Laizer, H., Chacha, M. and Ndakidemi, P.A. 2019. Farmers knowledge, perceptions and practices in managing weeds and insect pests of common bean in northern tanzania. *Sustainability*. **11**(15):4076. https://doi.org/10.3390/su11154076

Li, M., Sun, X., Yin, M., Shen, J. and Yan, S. 2023. Recent advances in nanoparticle-mediated co-delivery system: a promising strategy in medical and agricultural field. *International Journal of Molecular Sciences*. **24**(6): 5121. https://doi.org/10.3390/ijms24065121

Li, Y., Zhang, P., Li, M., Shakoor, N., Adeel, M., Zhou, P., Guo, M., Jiang, Y., Zhao, W., Lou, B. and Rui, Y. 2022. Application and mechanisms of metal-based nanoparticles in the control of bacterial and fungal crop diseases. *Pest Management Science*. **79**(1): 21-36. https://doi.org/10.1002/ps.7218

Morejon B., Pilaquinga F., Domenech F., Ganchala D., Debut A. and Neira M. 2018. Larvicidal activity of silver nanoparticles synthesized using extracts of *Ambrosia arborescens* (Asteraceae) to control *Aedes aegypti L.* (Diptera: Culicidae). *Journal of Nanotechnolgy*. https://doi.org/10.1155/2018/6917938

Murray, R.K., Granner, D.K, Mayes, P.A. and Rodwell, V.W. 2000: *Harper's Biochemistry*. 25th Edition, McGraw-Hill, Health Profession Division, New York, 225.

Ndakidemi, B., Mtei, K. and Ndakidemi, P. 2016. Impacts of synthetic and botanical pesticides on beneficial insects. *Agricultural Sciences*. **7**(6): 364-372. https://doi.org/10.4236/as.2016.76038

Noda, H., Kawai, S., Koizumi, Y., Matsui, K., Zhang, Q., Furukawa, S., … and Mita, K. 2008. Annotated ESTs from various tissues of the brown planthopper *Nilaparvata lugens*: A genomic resource for studying agricultural pests. *BMC Genomics*. **9**(1): 117. https://doi.org/10.1186/1471-2164-9-117

Paradva, K.C. and Kalla, S. 2023. Nanopesticides: A review on current research and future perspective. *Chemistry selec*t. https://doi.org/10.1002/slct.202300756

Parry, H.R. and Schellhorn, N.A. 2013. The use of models to explore IPM strategies and design pest suppressive landscapes for sustainable agricultural practice. *20th International Congress on Modelling and Simulation, Adelaide, Australia, 1–6 December 2013*. https://doi.org/10.36334/modsim.2013.h12.parry

Pittarate, S., Rajula, J., Rahman, A., Vivekanandhan, P., Thungrabeab, M., Mekchay, S. and Krutmuang, P. 2021. Insecticidal effect of zinc oxide nanoparticles against *Spodoptera frugiperda* under laboratory conditions. *Insects*. **12**(11): 1070. https://doi.org/10.3390/insects12111017

Ragaei, M. and Sabry, A.K.H. 2014. Nanotechnology for insect pest control. *International Journal of Science, Environment and Technology*. **3**(2):528–545.

Rai, M., Ingle, A. P., Pandit, R., Paralikar, P., Shende, S., Gupta, I., … and Silva, S.S.D. 2018. Copper and copper nanoparticles: role in management of insect-pests and pathogenic microbes. *Nanotechnology Reviews*. **7**(4), 303-315. https://doi.org/10.1515/ntrev-2018-0031

Raliya, R., Saharaņ, V. and Dimkpa, C.O. 2017. Nanofertilizer for precision and sustainable agriculture: Current state and future perspectives. *Journal of Agricultural and Food Chemistry*. **66**(26): 6487-6503. https://doi.org/10.1021/acs.jafc.7b02178

Ramanujam, B., Rangeshwaran, R., Sivakumar, G., Mohan, M. and Yandigeri, M. 2014. Management of insect pests by microorganisms. *Proceedings of the Indian National Science Academy*. **80**(2), 455. https://doi.org/10.16943/ptinsa/2014/v80i2/3

Riyaz, M., Hassan, S. and Rather, G.A. 2022. Revolutionizing integrated pest management using nanobiotechnology: A novel approach to curb overuse of synthetic insecticides. https://doi.org/10.5772/intechopen.101155

Rodrigues, T. and Figueira, A. 2016. Management of insect pest by RNAi - A new tool for crop protection. https://doi.org/10.5772/61807

Sabbour, M.M.A. 2020. Efficacy of nano-formulated certain essential oils on the Red flour beetle *Tribolium castaneum* and Confused flour beetle, *Tribolium confusum* (Coleoptera: Tenebrionidae) under laboratory and storage conditions. *Bulletin of the National Research Centre*. **44:** https://doi.org/10.1186/s42269-020-00336-6

Sahayaraj, K., Madasamy, M. and Radhika, S.A. 2016. Insecticidal activity of bio-silver and gold nanoparticles against *Pericallia ricini* Fab. (Lepidaptera: Archidae). *Journal of Biopesticides.* **9**(1):63-72. https://doi.org/10.57182/jbiopestic.9.1.63-72

Saleem, S., Bytesnikova, Z., Richtera, L. and Pokluda, R. 2021. The Effects of *Serendipita indica* and Guanidine-modified nanomaterial on growth and development of cabbage seedlings and black spot infestation. *Agriculture.* **11**(12):1295. https://doi.org/10.3390/agriculture11121295

Santos, T., Silva, T., Cardoso, J., Albuquerque-Júnior, R., Zielińska, A., Souto, E., … and Mendonça, M. 2021 Biosynthesis of silver nanoparticles mediated by entomopathogenic fungi: Antimicrobial resistance, nanopesticides, and toxicity. *Antibiotics*. **10**(7), 852. https://doi.org/10.3390/antibiotics10070852

Shahid, M., Ullah, U., Khan, W., Saeed, S. and Razzaq, K. 2021. Application of nanotechnology for insect pests management: a review. *Journal of Innovative Sciences*, **7**(1): 28-39. https://doi.org/10.17582/journal.jis/2021

Singh, R., Shedbalkar, U.U., Wadhwani, S.A. and Chopade, B.A. 2015. Bacteriagenic silver nanoparticles: synthesis, mechanism, and applications. *Applied microbiology and biotechnology*. **99**(11): 4579–4593. https://doi.org/10.1007/s00253-015-6622-1

Siva C. and Kumar M.S. 2015. Pesticidal activity of eco-friendly synthesized silver nanoparticles using *Aristolochia indica* extract against *Helicoverpa armigera* Hubner (Lepidoptera: Noctuidae). *International Journal of Advanced Science and Technology Research*. **2**:197-226

Sivapriyajothi S., Kumar P.M., Kovendan K., Subramaniam J. and Murugan K. 2014. Larvicidal and pupicidal activity of synthesized silver nanoparticles using *Leucas aspera* leaf extract against mosquito vectors, *Aedes aegypti* and *Anopheles stephensi*. *Journal of Entomological and Acarological Research*. **46**(2):77-84

Smedt, C.D., Someus, E., and Spanoghe, P. 2015. Potential and actual uses of zeolites in crop protection. *Pest Management Science*. **71**(10), 1355-1367. https://doi.org/10.1002/ps.3999

Stadler, T., Buteler, M. and Weaver, D.K. 2010. Novel use of nanostructured alumina as an insecticide. *Pest Management Science*. **66**(6):577-9. https://doi.org/10.1002/ps.1915

Strambeanu, N., Demetrovici, L., Dragos, D. and Lungu, M. 2014. Nanoparticles: definition, classification and general physical properties. Nanoparticles' Promises and Risks. Springer, Cham. https://doi.org/10.1007/978-3-319-11728-7_1

Sun, Y. and Xia, Y. 2002. Shape-controlled synthesis of gold and silver nanoparticles. *Science.* **298**: 2176-2179. https://doi.org/10.1126/science.1077229

Wang, X., Xu, J., Sun, T., and Ali, S. 2021. Synthesis of *Cordyceps fumosorosea*-biochar nanoparticles and their effects on growth and survival of *Bemisia tabaci* (Gennadius). *Frontiers in Microbiology*. 12:630220. https://doi.org/10.3389/fmicb.2021.630220

Wang, X., Xu, J., Wang, X., Qiu, B., Cuthbertson, A.G.S., Du, C., Wu, J. and Ali, S. 2019. *Isaria fumosorosea*-based zero-valent iron nanoparticles affect the growth and survival of sweet potato whitefly, *Bemisia tabaci* (Gennadius). *Pest Management Science*. **75**(8):2174-2181. https://doi.org/10.1002/ps.5340

Waterfield, G. and Zilberman, D. 2012. Pest management in food systems: An economic perspective. *Annual Review of Environment and Resources.* **37**:223-245. https://doi.org/10.1146/annurev-environ-040911-1056288

Worrall, E., Hamid, A., Mody, K.T., Mitter, N. and Pappu, H.R. 2018. Nanotechnology for plant disease management. *Agronomy*. **8**(12):285. https://doi.org/10.3390/agronomy8120285

Wu, J., Du, C., Zhang, J., Yang, B., S. Cuthbertson, A.G. and Ali, S. 2021. Synthesis of *Metarhizium anisopliae*–chitosan nanoparticles and their pathogenicity against *Plutella xylostella* (Linnaeus). *Microorganisms*. **10**(1):1. https://doi.org/10.3390/microorganisms10010001

Xu, J., Zhang, K., S. Cuthbertson, A.G., Du, C. and Ali, S. 2020. Toxicity and biological effects of *Beauveria brongniartii* FeO nanoparticles against *Spodoptera litura* (Fabricius). *Insects*. **11**(12):895. https://doi.org/10.3390/insects11120895

Yan, S., Ren, B. and Shen, J. 2020. Nanoparticle-mediated double-stranded RNA delivery system: A promising approach for sustainable pest management. *Insect Science*. **28**(1): 21-34. https://doi.org/10.1111/1744-7917.12822

Yang, J., Yan, S., Xie, S., Yin, M., Shen, J., Li, Z., Zhou, Y. and Duan, L. 2022. Construction and application of star polycation nanocarrier-based microRNA delivery system in *Arabidopsis* and Maize. *Journal of Nanobiotechnology*. **20**:219. https://doi.org/10.1186/s12951-022-01443-4

Yasir Wasaya, T.A., Naeem Sarwar, O.F., Sheikh, G.R. and Baloch, A.W. 2020. Improving growth and yield of mungbean (*Vigna radiata*) through foliar application of silver and zinc nanoparticles. *Pure and Applied Biology*. **9**(1): 790-797. https://doi.org/10.19045/bspab.2020.90085

Zayed, M.S. 2020. Evaluation of novel nanoparticles against *Tetranychus urticae* and its predatory mite *Amblyseius gossipi*. *Zagazig Journal of Agricultural Research*. **47**(4): 951-961. https://doi.org/10.21608/zjar.2020.110323

Zhao, S., Liu, J., Bai, Z., Hu, C. and Jin, Y. 2022. Crop pest recognition in real agricultural environment using convolutional neural networks by a parallel attention mechanism. *Frontiers in Plant Science.* 13:839572. https://doi.org/10.3389/fpls.2022.839572