



Nanotechnology in Entomology: Novel Approaches for Sustainable Insect Pest Management

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INTRODUCTION

Nanotechnology has emerged as one of the promising technological approaches for addressing these challenges. Nanotechnology involves the design, synthesis, characterization and application of materials with dimensions generally within the nanoscale range. At this scale, materials can exhibit physicochemical characteristics that differ from their bulk forms. Their high surface-area-to-volume ratio, surface reactivity, adsorption capacity, tunable surface charge and ability to encapsulate or carry active compounds provide new possibilities for agricultural pest management. In entomology, these properties can be exploited to develop nano-insecticides, controlled-release formulations, botanical nano formulations and molecular delivery systems.

The importance of nanotechnology is not limited to increasing the toxicity of insecticides. One of its most important contributions is the improvement of pesticide delivery. Nanocarriers can protect active ingredients against ultraviolet radiation, oxidation and environmental degradation while improving their dispersion, adhesion and persistence on plant surfaces. Controlled-release systems can potentially provide a more gradual release of the active ingredient, thereby reduce unnecessary losses and increasing the duration of pest control. Recent research has also expanded the application of nanoparticles toward molecular pest management, particularly through the delivery of double-stranded RNA for RNA interference-based control.

2. Concept of Nanotechnology in Entomology

Nanotechnology in entomology refers to the application of nanoscale materials and nano-enabled delivery systems for the detection, monitoring, prevention and management of insect pests. Nano-enabled pest-management systems can broadly be divided into two categories. The first category consists of nanoparticles that possess intrinsic insecticidal properties, while the second includes nanoparticles that function as carriers for conventional insecticides, botanical compounds, essential oils, pheromones or biological molecules.

3. Need for Nanotechnology in Sustainable Insect Pest Management

The increasing occurrence of insecticide resistance is one of the major challenges facing modern agriculture. Continuous application of insecticides with similar modes of action creates selection pressure that favours resistant individuals.

Over time, resistant populations increase and the effectiveness of the insecticide

declines. Nanotechnology may contribute to resistance management by improving delivery efficiency, facilitating combinations of active ingredients and enabling multiple modes of action. However, nano-insecticides must also be incorporated into resistance-management strategies because repeated exposure to the same nanoparticle or nanoformulation could potentially result in adaptive response.



4. Major Nanomaterials Used in Insect Pest Management

A diverse range of nanomaterials has been investigated for insect pest management. Metallic nanoparticles such as silver, copper and zinc oxide have attracted considerable attention because of their biological activity and ability to interact with insect tissues. Silver nanoparticles, for example, have demonstrated

insecticidal effects against several insect species and may cause oxidative stress, membrane damage and enzyme disruption. Zinc oxide nanoparticles can generate reactive oxygen species and may interfere with metabolic processes. Copper-based nanoparticles have also demonstrated insecticidal and antimicrobial properties.



Table 1: Major nanomaterials and their potential applications in entomology

Nanomaterial	Major characteristics	Potential entomological application
Silver nanoparticles (AgNPs)	High surface activity, antimicrobial and insecticidal properties	Direct insecticidal activity
Silica nanoparticles	High surface area, porous structure, modifiable surface	Insecticide carriers, cuticle disruption
Zinc oxide nanoparticles	Semiconductor properties, ROS generation	Direct insecticidal activity
Titanium dioxide nanoparticles	Photocatalytic activity	Insecticidal and protective applications
Alumina nanoparticles	High surface activity	Stored-product pest management
Copper nanoparticles	Metal-based activity	Insecticidal formulations
Chitosan nanoparticles	Biodegradable and bioactive	Botanical and synthetic insecticide delivery
Polymeric nanoparticles	Controlled and tunable release	Delivery of insecticides and RNA
Nanoemulsions	Improved dispersion and stability	Essential oils and botanical insecticides
Lipid nanoparticles	Biocompatibility and encapsulation	Delivery of hydrophobic compounds
Carbon-based nanomaterials	Large surface area and adsorption capacity	Experimental pesticide delivery
Nanoclays/zeolites	Adsorption and controlled release	Pesticide carriers

5. Green Synthesis of Nanoparticles

Green synthesis uses biological materials such as plants, microorganisms, fungi, algae and agricultural residues to produce nanoparticles. Plant extracts are particularly attractive because they contain phenolics, flavonoids, proteins, terpenoids and other secondary metabolites that can act as reducing and stabilizing agents. During synthesis, these compounds can reduce metal ions and facilitate the formation and stabilization of nanoparticles.

6. Mechanisms of Action of Nano-Insecticides

The insecticidal activity of nanoparticles can involve several mechanisms operating simultaneously. One important mechanism is interaction with the insect cuticle. The cuticle represents the primary protective barrier of insects and plays a critical role in maintaining water balance. Certain nanoparticles can adhere to the cuticular surface and interfere with the wax layer. Physical disruption of this protective

layer may increase water loss and contribute to dehydration.

7. Nanoformulation of Botanical Insecticides

Botanical insecticides have long been considered an important component of environmentally compatible pest management. Plant-derived compounds such as neem constituents, essential oils, terpenoids and phenolics may exhibit insecticidal, repellent, antifeedant or growth-regulating effects. However, their agricultural application is often restricted by high volatility, poor water solubility, rapid photodegradation and short persistence.

8. Chitosan Nanoparticles in Insect Pest Management

Chitosan is a natural polysaccharide derived primarily from chitin and possesses several properties that make it attractive for sustainable agricultural applications. It is biodegradable, relatively biocompatible and capable of

forming films, gels, emulsions and nanoparticles. Chitosan also exhibits biological activity and may influence plant defence responses.

9. Silver Nanoparticles in Insect Pest Management

Silver nanoparticles are among the most widely investigated metallic nanoparticles for biological applications. Their insecticidal activity has been reported against several economically important insect pests. The biological effects of silver nanoparticles may include oxidative stress, membrane disruption, enzyme inhibition, mitochondrial dysfunction and interference with cellular processes.

10. Silica Nanoparticles in Insect Pest Management

Silica nanoparticles possess high surface area, adsorption capacity and structural versatility. These characteristics make them suitable for both direct insecticidal activity and pesticide delivery. Certain silica materials can interact with the insect cuticle and contribute to physical damage and dehydration. Engineered silica particles can also be modified to carry insecticides and release them gradually.

11. Zinc Oxide and Metal Oxide Nanoparticles

Zinc oxide nanoparticles are particularly interesting because zinc is an essential micronutrient for plants and organisms at appropriate concentrations. However, the fact that zinc is an essential element does not mean that ZnO nanoparticles are inherently safe. Nanoscale materials may behave differently from dissolved zinc ions, and their toxicity depends strongly on concentration and exposure conditions.

12. Nanoparticle-Mediated RNA Interference

Nanotechnology has opened an important new direction in molecular insect pest management through nanoparticle-mediated RNA interference. RNAi is a biological process in which double-stranded RNA triggers sequence-specific degradation or suppression of

complementary messenger RNA. Silencing an essential gene can interfere with insect development, reproduction, metabolism or survival.

13. Controlled-Release Nanoformulations

Controlled release is one of the most important advantages offered by nanotechnology. Conventional pesticide applications often result in rapid release of the active ingredient immediately after spraying. A portion of the material may subsequently be lost through evaporation, runoff, photodegradation or other environmental processes.

Nanocarriers can be designed to retain the active ingredient and release it gradually. The rate of release can potentially be modified through changes in polymer composition, particle size, surface chemistry and environmental responsiveness. Stimuli-responsive formulations may release active ingredients in response to pH, temperature, enzymes, moisture, light or other conditions.

15. Nano-Enabled Pheromone Delivery

Nanotechnology could potentially improve pheromone delivery by encapsulating pheromones within controlled-release systems. Such formulations may allow more uniform and prolonged release while reducing rapid volatilization. Nano-enabled pheromone systems could consequently become useful components of environmentally compatible pest-management programmes.

16. Nanotechnology and Integrated Pest Management

Nanotechnology should be integrated into existing integrated pest management rather than used as an isolated technology. IPM combines cultural, mechanical, biological, behavioural and chemical methods with pest monitoring and economic threshold principles. Nano-insecticides can potentially be introduced when monitoring indicates that pest populations have reached economically important levels.

The integration of nanotechnology with biological control is particularly important. Selective nanoformulations could

potentially reduce exposure of predators and parasitoids compared with broad-spectrum conventional insecticides, but this assumption must be confirmed through experimental

studies. Nanoformulations should therefore be tested against key natural enemies before field adoption.



17. Nanotechnology and Precision Agriculture

Precision agriculture provides an important technological environment for nano-enabled pest management. Remote sensing, drones, artificial intelligence, machine learning and IoT sensors can provide information on pest distribution and infestation intensity. Nanoformulations can then potentially be applied only to affected areas.

For example, an AI-enabled image-recognition system may identify an insect outbreak from field images. GIS can map the affected area, while a decision-support system can determine whether the pest population has crossed an economic threshold. A UAV or precision sprayer may subsequently deliver the selected nanoformulation to the affected area.

21. Advantages of Nanotechnology in Sustainable Pest Management

The major advantage of nanotechnology lies in its ability to modify how insecticidal compounds are delivered. Nanoformulations may improve the solubility, stability, dispersion and bioavailability of poorly soluble

compounds. Controlled-release systems can potentially increase the duration of biological activity while reducing the frequency of application. Nanoencapsulation may protect botanical compounds from environmental degradation, making plant-derived pesticides more practical.

Nanotechnology also provides opportunities for precision delivery of biological molecules. Nanoparticle-mediated RNAi is particularly promising because it may allow species-specific gene silencing. In addition, nano-enabled pheromone systems could improve behavioural pest management through controlled release.

22. Major Limitations and Challenges

Production cost is also an important limitation. The synthesis, purification, characterization and formulation of nanoparticles may be more expensive than conventional pesticide production. The technology will become commercially viable only when improvements in pest control and reductions in application frequency compensate for additional formulation costs.

Regulatory uncertainty is another important issue. Nano-enabled pesticides may require assessment beyond conventional pesticide registration because their environmental behaviour can be influenced by particle size, surface properties and transformation. Clear guidelines are therefore required for registration, residue assessment, worker safety and environmental monitoring.

23. Future Perspectives

The future development of nanotechnology in entomology is expected to move towards greater precision, selectivity and environmental compatibility. One important direction is the development of biodegradable nanocarriers derived from natural polymers such as chitosan and other biopolymers. Such materials may provide controlled delivery while reducing concerns associated with persistent inorganic nanoparticles.

Green nanotechnology is expected to become increasingly important. Plant-mediated nanoparticle synthesis, biodegradable carriers and agricultural-waste-derived nanomaterials could contribute to more sustainable production systems. However, green synthesis must be accompanied by rigorous toxicological testing to ensure that the final product is genuinely environmentally compatible.

CONCLUSION

Nanotechnology has emerged as a promising frontier in modern agricultural entomology and offers new possibilities for improving the efficiency, precision and sustainability of insect pest management. The development of nano-insecticides, nanoemulsions, polymeric nanocarriers, chitosan nanoparticles, metallic nanoparticles, silica-based systems, controlled-release formulations and nanoparticle-mediated RNAi has expanded the technological options

available for managing economically important insect pests.

Future research should focus on biodegradable nanomaterials, green synthesis, precision delivery, smart controlled-release systems, nano-RNAi, nano-enabled pheromones and integration with artificial intelligence and precision agriculture. With appropriate risk assessment, field validation and regulatory oversight, nanotechnology has considerable potential to contribute to the transition from broad-spectrum pesticide dependence towards a more targeted, efficient and environmentally responsible system of insect pest management.

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