Nanoparticle-Mediated Control of Storage Pests: A Review

G. Nathiya, D. Vijaya Lakshmi, S. Thenmozhi, G.V. Krishna Teja Sree, S. Kavya, K. Elumalai

Unit of Entomotoxicity, Department of Zoology, Government Arts College (Autonomous), Nandanam, Chennai-600035, Tamil Nadu, India

Abstract

Managing stored product pests continues to be a major challenge for global food security, as traditional synthetic pesticides face rising issues such as insect resistance, environmental contamination, and human health hazards. This review explores the emerging use of nanotechnology as a revolutionary method for pest control, focusing on nanoparticle-based formulations like metal nanoparticles (silver, copper, zinc oxide), metal oxide nanoparticles (silica, titanium dioxide), and polymeric nanoparticles from natural biopolymers. Nanopesticides provide benefits over traditional pesticides through greater surface area, better bioavailability, controlled release, and improved stability of active agents. Eco-friendly green synthesis methods using plant extracts create alternatives that reduce toxic residues, while still effectively targeting key storage pests like *Sitophilus oryzae*, *Tribolium castaneum*, *Callosobruchus maculatus*, and *Rhyzopertha dominica*. Their actions include physical damage to the cuticle, oxidative stress, enzyme inhibition, and disruption of reproductive processes. Although laboratory results are promising, challenges such as scaling up production, regulatory approval, environmental impact assessments, and non-target effects remain. Future directions highlight the integration of nanoformulations into comprehensive Integrated Pest Management (IPM), development of stimuli-responsive delivery systems, and safety evaluation frameworks. Combining nanotechnology with sustainable agriculture offers promising opportunities to reduce post-harvest losses while addressing environmental and health concerns linked to conventional chemical controls.

Keywords: Nanopesticides, Stored product pests, Green synthesis, Integrated Pest Management (IPM)

1.0 Introduction

Global food security depends on reducing post-harvest losses, yet conventional chemical control techniques are becoming less successful due to insect resistance and environmental problems. (Jasrotia and others, 222). Consequently, nanotechnology has emerged as a transformative alternative, leveraging unique physicochemical properties to enhance the delivery, stability, and efficacy of pest management agents (Kamalakannan *et al*., 2025). By facilitating controlled release and increasing surface-to-volume ratios, these nano-formulations—including nano-emulsions and micelles—overcome the limitations associated with traditional synthetic pesticides (Anjana, Ahmad and Mir, 2025). Furthermore, the green synthesis of metallic nanoparticles using plant-derived bioactive compounds offers a sustainable pathway to developing eco-friendly nano-biopesticides that minimize the toxic residues associated with conventional chemical interventions (Baliyarsingh and Pradhan, 2023). These advanced nanomaterials, ranging from metal oxides such as silver and zinc oxide to silica-based carriers, demonstrate superior bioefficacy against diverse stored-product insects by disrupting physiological and metabolic processes (Jayapradha *et al*., 2025).

1.1 Current Challenges in Storage Pest Management

Persistent post-harvest losses continue to threaten global food security, with regional impacts varying significantly between temperate zones and tropical climates. Damage from insect species and rodents accumulates and is further exacerbated by the evolution of pesticide resistance and the unpredictable effects of climate change on pest population dynamics (Mishra *et al*., 2024). Furthermore, reliance on synthetic chemicals has contributed to significant biodiversity loss and lingering toxicity in consumable produce, necessitating a transition toward precision-based integrated pest management strategies (Yousef *et al*., 2023). In this context, integrating nanobiosensors for real-time monitoring of grain storage environments enables early detection of pest infestations, thereby enabling targeted interventions that reduce the frequency and volume of pesticide applications (Raypuriya *et al*., 2025). Despite these technological strides, the widespread commercial adoption of such nanomaterials remains constrained by elevated production costs and the need for comprehensive toxicological assessments of their long-term health implications (Abbas *et al*., 2022). Additionally, standardizing regulatory frameworks and environmental safety guidelines is essential to ensure that the deployment of these nano-enabled solutions does not inadvertently introduce new ecological risks (Ibrahim *et al*., 2021; Ghareeb *et al*., 2025).

1.2 Economic Impact of Storage Pests

The quantitative damage caused by insect feeding during storage can result in weight losses of 8% to 22% per grain, significantly devaluing agricultural commodities and compromising food quality (Ibrahim *et al*., 2024). Beyond these quantitative reductions, direct damage to the endosperm and embryos promotes grain rot and introduces unpleasant odors, rendering the supply unfit for consumption (Haroun *et al*., 2023). Specifically, infestations by pests such as *Sitophilus oryzae and Tribolium castaneum* impose substantial economic burdens, necessitating more effective protectant alternatives to prevent these pervasive post-harvest losses (Haroun *et al*., 2023). Moreover, these arthropod-induced losses are exacerbated by the subsequent proliferation of fungal pathogens and mites, which thrive in the microclimatic conditions created by insect-generated hotspots (Guru *et al*., 2022). These cumulative losses, which can reach up to 60% in some developing nations, underscore the critical need for advanced intervention strategies to secure global food supplies (Nawaz *et al*., 2023). The high costs associated with conventional pest management methods, which can reach up to US$ 50 billion annually, further justify the economic transition toward innovative, nanotechnology-based interventions to minimize these financial burdens (Baker *et al*., 2017).

1.3 Limitations of Conventional Pest Control Methods

Traditional fumigation techniques often rely on chemical agents to which many storage-dwelling *coleopteran* species have already developed significant resistance (Gupta *et al*., 2023). This widespread resistance necessitates rotating among diverse pesticide groups to prevent the emergence of new, hardier strains (Gupta *et al*., 2023). However, the commercialization of nanopesticides faces significant hurdles, including high development costs, complex regulatory approval processes, and a lack of standardized methods for assessing long-term ecological risks (Camara *et al*., 2019; An *et al*., 2022). Moreover, the intensive use of conventional fumigants such as methyl bromide and aluminum phosphide poses severe hazards to human health and the environment, often requiring stringent government oversight.

2.0 Nanotechnology in Pest Control: An Overview

Nanotechnological applications utilize inorganic materials such as silver, titanium dioxide, and aluminum oxide to offer durable, long-lasting protection against pests like *Sitophilus oryzae* (Ram, Kumar and Kumar, 2014). These engineered particles penetrate the insect cuticle through improved adhesion and absorption, disrupting key physiological and metabolic processes (Choupanian and Omar, 2018; Falsini *et al*., 2024). Notably, silica nanoparticles outperform bulk materials because of their high surface-to-volume ratio, enabling effective control of stored-product insects such as S. *oryzae* and R. dominica on cereals (Draz *et al*., 2023). The effectiveness of these nanomaterials depends on particle size, with 12–60 nm particles showing strong insecticidal activity against larval and adult stages of pests like *Callosobruchus maculatus* (Arumugam *et al*., 2015). These particles cause physical disruptionand induce systemic oxidative stress, increasing reactive oxygen species, damaging cells, and causing rapid insect mortality (Ansari *et al*., 2025).

Green-synthesized nanoparticles, such as those made from leaf extracts, present a sustainable alternative that achieves high pest mortality while reducing environmental impact (Whyte and Shand, 1970). However, scaling up nanoproduct production faces technological hurdles related to particle dispersion, ingredient delivery, and product stability during storage (Jabran *et al*., 2024). The absence of international standards for assessing the environmental and human health risks of these nanomaterials complicates the creation of global regulations (Campos *et al*., 2018). Current research aims to establish biosafety benchmarks for silica-based nanomaterials, which organizations like the World Health Organization have identified as potentially safe for agricultural pest management (Deka *et al*., 2021). Additionally, these materials are being used for structural protection, such as coating insect-proof nets with SiO2 nanoparticles to allow ventilation while blocking pests like *Aphis fabae* and *T. confusum* (Agrafioti *et al*., 2020). Advances in nano-encapsulation have also enabled the development of chitosan-based systems loaded with essential oils, offering a combined insecticidal effect through volatile botanical compounds and improved cuticle penetration (Singh *et al*., 2024).

3.0 Definition and Types of Nanoparticles

Nanopesticides are broadly classified as formulations containing components in the nanometer size range, often characterized by unique properties that enhance the biological activity of active ingredients against specific insect targets (Omara *et al*., 2019; Manna *et al*., 2023). These systems are categorized by their structural composition, which encompasses inorganic agents such as metallic silver, iron, and copper, as well as organic platforms such as polymer-based nanogels and lipid-encapsulated formulations (Deka *et al*., 2021; Shahid *et al*., 2023). These systems function as sophisticated delivery vehicles, using nanosized droplets or encapsulated carriers to optimize concentration and sustain the release of active insecticidal compounds at the target site (Mittal *et al*., 2020). Additionally, these platforms include nanoemulsions, nanodispersions, and solid-liquid nanoparticles, which significantly increase the potency of active agents compared to their bulk counterparts (Kumari *et al*., 2023).

These advanced delivery systems frequently incorporate stimuli-responsive mechanisms, such as polymer-based platforms, to enable the controlled release of pesticides in response to environmental fluctuations, including pH and moisture (Kah *et al*., 2021; Shekhar *et al*., 2021). Moreover, incorporating surfactants into these nanoemulsions enhances the solubility and uniform coverage of hydrophobic active ingredients, thereby reducing the need for high-volume applications and slowing the development of physiological resistance (Chhipa, 2017; Thabet *et al*., 2021). Furthermore, these delivery systems protect bioactive agrochemicals from rapid environmental degradation, such as photo-oxidation or thermal instability, which significantly prolongs their residual efficacy in storage environments (Shoaib *et al*., 2018; Ayilara *et al*., 2023).

4.0 Mechanisms of Nanoparticle Action

The mode of action for these materials primarily involves physical disruption of the insect cuticle through abrasive action or the blockage of spiracles, leading to desiccation and asphyxiation (González *et al*., 2013). Concurrently, ingested nanoparticles exploit the insect's high surface-to-volume ratio to enhance the bioavailability of bioactive compounds, facilitating deeper penetration into tissues and triggering metabolic disruption (Manna *et al*., 2023; Luneja and Mkindi, 2025). Specifically, these nanostructured carriers improve droplet adhesion and dispersion on treated surfaces, ensuring that the active ingredients reach target sites at the lowest effective concentrations (Jiang *et al*., 2021; Shelar *et al*., 2023). These nano-formulations further leverage slow-release properties and enhanced stability to provide long-term protection, ensuring that minimal dosages remain potent for extended periods within storage facilities (Mgadi *et al*., 2024). By transitioning from conventional delivery to these intelligent nanoscale platforms, researchers can achieve up to a 31.5% increase in overall pesticidal efficacy compared to non-nanoscale analogues.

This improvement in performance is largely attributed to the ability of nanocarriers to protect labile active ingredients from degradation, while simultaneously enabling stimulus-responsive release profiles that ensure targeted action (Wang *et al*., 2022; Shangguan *et al*., 2024). Furthermore, these systems facilitate the deployment of poorly water-soluble pesticides, significantly augmenting their bioavailability while reducing the necessity for toxic adjuvants that may otherwise harm non-target organisms (Iavicoli *et al*., 2017; Osman *et al*., 2024). Nanoemulsions, in particular, have demonstrated superior kinetic stability and effectiveness against major grain storage pests like the rice weevil and red flour beetle by optimizing droplet size to maximize cuticular absorption (McClements *et al*., 2021), (Devi *et al*., 2024). For instance, the encapsulation of garlic essential oil in polyethylene glycol carriers has achieved an 80% mortality rate in red flour beetles, far outperforming the 11% efficacy observed with the essential oil alone (Gupta *et al*., 2021). Beyond direct toxicity, nano-encapsulated essential oils demonstrate significant repellent effects that prevent infestation, often attributed to the high mobility and chemical activity of their optimized droplet size (Ibrahim, 2019).

5.0 Effect of Nanoparticles on Storage Pests

Nanoparticles exert control over storage pests by altering the micro-environment of stored grains, where their small size and high dispersibility ensure uniform surface coverage without compromising the bulk density or physical integrity of the commodities (Hamel, Rozman and Liška, 2021). By integrating essential oils into these controlled-release nano-formulations, researchers can effectively prevent rapid vaporization and degradation, thereby enhancing the persistence of volatile botanical compounds (Sabbour and El-Aziz, 2019). This sustained release profile effectively mitigates the volatility of active terpenes, ensuring that compounds remain at toxicologically significant concentrations for extended intervals (Jampílek and Kráľová, 2015). Furthermore, these nanostructured matrices enhance the biodegradability and thermal stability of encapsulated bioactives, allowing for more consistent protection against diverse environmental stresses (Singh *et al*., 2023).

Specifically, nanoencapsulation has been shown to extend the period of toxicological contact for up to 24 weeks against pests such as *Tribolium castaneum* and *Rhizopertha dominica* (Garrido-Miranda, Giraldo and Schoebitz, 2022). Moreover, the application of these formulations directly onto grain stocks is facilitated by their favorable water-soluble characteristics, which allow for simple removal through aqueous washing without leaving harmful residues (Ikawati *et al*., 2020). Synergistic applications involving inorganic materials combined with entomopathogenic fungi, such as Beauveria bassiana, have also demonstrated success in suppressing beetle populations by creating multi-modal stress environments.

5.1 Insecticidal Efficacy of Nanoparticles

Recent investigations indicate that loading essential oils like coriander or caraway into nano-formulations significantly elevates mortality rates against *Tribolium castaneum* and *T. confusum* compared to free oil applications (Sabbour, 2020). These findings are complemented by evidence suggesting that polymeric encapsulation facilitates enhanced cuticular penetration, as the insect cuticle acts as a two-phased structure comprising distinct lipophilic and hydrophilic layers (Jesser *et al*., 2020). By leveraging amphiphilic nanocarriers, such as chitosan-based systems, researchers can effectively bridge this barrier to deliver lipophilic bioactive molecules directly into the hemolymph of the pest (DeVries, Trucksess and Jackson, 2002; Sabuncuoğlu, 2019). Additionally, the improved stability conferred by these carriers reduces the rate of premature evaporation and thermal degradation of volatile compounds, a common drawback when applying pure essential oils in storage facilities (Campos *et al*., 2018; Lammari *et al*., 2021).

Moreover, the encapsulation of volatile compounds, such as Artemisia essential oil, facilitates a controlled release mechanism that requires lower total dosing amounts to achieve comparable or superior mortality rates (Sabbour, 2019). Furthermore, the utilization of chitosan-based nanoparticles for *Carum copticum* oil has demonstrated increased mortality levels in *R. dominica* and *T. confusum* adults, proving that such delivery systems effectively overcome the inherent chemical instability of botanical volatiles (Ziaee, Takabi and Ebadollahi, 2023). Additionally, the physical mechanism of silica nanoparticles contributes to pest control by sorbing directly into the lipids of the insect cuticle, which disrupts their structural integrity and leads to dehydration-related mortality(Ibrahim, Elbehery and Samy, 2024).

5.2 Repellent Properties of Nanoparticles

Beyond their lethal potential, nanoparticle-based formulations act as potent deterrents by disrupting the chemical cues used by insects for host selection and pheromone-mediated aggregation (Sayed, Rizk and Sayed, 2023). Specifically, loading garlic and cinnamon oils into chitosan-based polymeric nanoparticles has been shown to enhance repellent and antinutritional activities against *Tribolium castaneum* through improved environmental stability and controlled-release kinetics (Khandehroo *et al*., 2024). This persistent release of bioactive constituents also extends the duration of protection, with studies reporting substantial increases in the half-life (PT_{50}) of essential oils when compared to their free-oil counterparts (Elbehery *et al*., 2025). Furthermore, the integration of these systems into grain storage protocols addresses the challenge of pesticide resistance by providing a multifaceted mode of action that prevents the rapid breakdown of active molecules (Ibrahim, 2019). In addition to these chemical strategies, mesoporous silica nanoparticles have proven effective due to their large surface area, which facilitates the adsorption of botanical insecticides and significantly shortens knockdown times for species such as *Callosobruchus chinensis* compared to bulk silica (Attia *et al*., 2023).

6.0 Types of Nanoparticles Used Against Storage Pests

6.1 Metal Nanoparticles

Silver and copper-based nanoparticles are frequently synthesized for their potent antimicrobial and insecticidal properties, which stem from the release of metal ions that disrupt critical metabolic enzymes within the pest's physiology. These metallic agents promote oxidative stress by generating reactive oxygen species, leading to severe cellular damage in pests such as *Sitophilus oryzae* (Rai *et al*., 2018). Furthermore, zinc oxide nanoparticles have been successfully evaluated for their ability to inhibit larval development by interfering with nutrient absorption and enzymatic activity (Omara *et al*., 2019). Similarly, aluminum and titanium dioxide nanoparticles have exhibited significant insecticidal potential, with laboratory and storage trials confirming that their application leads to marked increases in the mortality of *Sitophilus oryzae* over extended exposure periods (Kwenti, 2017).

6.2 Metal Oxide Nanoparticles

These materials, particularly silica-based nanostructures, are increasingly used due to their high surface-to-volume ratio, which enhances their efficacy in contact against pests such as *Rhizopertha dominica* and *Tribolium confusum* (Draz *et al*., 2023; Abd-Elnabi and Badawy, 2024). In particular, silica-based nanoparticles have demonstrated dose-dependent mortality in these species, with specific particle sizes showing heightened efficacy in protecting treated wheat and barley grains (Rastogi *et al*., 2019). Specifically, silica nanoparticles loaded with insecticides like chlorpyrifos have achieved complete mortality in *R. dominica* and *T. confusum* populations within hours of exposure, highlighting their utility as potent, low-dosage alternatives to conventional chemical treatments (Abd-Elnabi and Badawy, 2024). Furthermore, comparative assessments of various silica forms, such as Aerosil 200 and bio-silica, have revealed that their insecticidal performance is highly dependent on formulation-specific physical properties, with certain chemical silica variants achieving superior efficacy against pests like *Callosobruchus maculatus* (Ziaee and Zahra, 2016; Salem, 2020).

6.3 Polymeric Nanoparticles

These systems leverage biodegradable matrices—such as chitosan, alginate, or polylactic acid—to encapsulate volatile botanical compounds, effectively protecting sensitive active ingredients from environmental degradation (Salem, Hamzah and El-Taweelah, 2015; Miksanek and Tuda, 2023). By utilizing polythylene glycol-coated nanoparticles, researchers can further enhance the delivery efficacy of loaded essential oils, as evidenced by the high mortality rates observed against red flour beetles in stored grain products (Khater, Govindarajan and Benelli, 2017). Beyond their delivery functions, these biopolymer carriers are increasingly recognized for their ability to significantly reduce progeny production, thereby limiting the generational growth of internal grain feeders like Sitophilus species (Stadler *et al*., 2011). Beyond these established delivery mechanisms, research has increasingly focused on the comparative efficacy of inert nanoinsecticides, such as nano-silica and zinc nanoparticles, which have demonstrated substantial lethal potential against major internal feeders like *Sitophilus granarius* and *Trogoderma granarium* (Raduw and Mohammed, 2020; Rouhani *et al*., 2023).

6.4 Nanoencapsulated Plant Extracts

These delivery systems enhance the solubility and bioavailability of botanical compounds, allowing for improved penetration into agricultural substrates such as corn and rape seeds (Madanayake, Hossain and Adassooriya, 2021). Beyond simple stabilization, nanoencapsulation enables controlled release via mechanisms such as diffusion, dissolution, and biodegradation, ensuring consistent protection against both primary and secondary storage pests (Fathy, 2012). For instance, silver nanoparticles synthesized from *Annona reticulata* leaf extracts have been demonstrated to exert significant insecticidal activity against Sitophilus oryzae (Dantas *et al*., 2021). Similarly, the green synthesis of nanoparticles using plant-derived phytochemicals minimizes the toxicity associated with traditional chemical insecticides, offering a sustainable alternative for protecting stored commodities (Rankić *et al*., 2021). Furthermore, the application of silica nanoparticles, both as standalone agents and as carrier systems, has shown remarkable persistence in various legumes, achieving total mortality in *Callosobruchus maculatus* across extended storage intervals (Irani, Karimpour and Ziaee, 2023).

7.0 Factors Influencing Nanoparticle Efficacy

7.1 Nanoparticle Size and Shape

The high surface-to-volume ratio associated with smaller particle dimensions facilitates more efficient adherence to the insect cuticle, significantly increasing the probability of contact-induced mortality (Shahid, Faizan and Raza, 2023). This enhanced reactivity allows finer particles, such as graphene quantum dots, to interact more effectively with the protective cuticular wax layer, thereby improving insecticidal performance compared to larger formulations (Ahmad *et al*., 2024). Additionally, the morphological properties of these particles—ranging from spheres to irregularly shaped, finely divided structures—determine their ability to cause micro-wounds and subsequent dehydration by absorbing epicuticular lipids (Ibrahim and Salem, 2019). Furthermore, the synthesis environment, such as the use of specific plant extracts for bio-reduction, can dictate the crystalline orientation and stability of the resulting particles, which directly influences their penetration depth into the target insect's physiological barriers (Helmy *et al*., 2022).

7.2 Concentration and Application Method

The amount of nanomaterials used is crucial for effectiveness: too little may not produce sufficient mortality, whether physical or chemical, while too much can cause unnecessary contamination (Negi and Moses, 2025). The method of application—such as grain coating, direct surface treatment, or residual spraying—also greatly influences the bioavailability of the nanoparticles and their effect on target species (Khorrami *et al*., 2019). For instance, silica nanoparticles at just 200 ppm can effectively kill pests and protect seeds in stored pulses, highlighting the need for precise dosing (Abdou *et al*., 2022). Likewise, zinc-based nanomaterials show a dose-dependent increase in efficacy, with higher concentrations in substrates like cowpeas achieving mortality rates up to 97.3% (Sohrabi *et al*., 2024).

7.3 Environmental Conditions

Ambient factors such as humidity, temperature, and light exposure significantly influence the degradation rates and stability of active ingredients, often necessitating precise formulation to maintain long-term persistence in storage environments (Xu *et al*., 2010). Specifically, lower relative humidity levels tend to exacerbate the dehydrating effects of abrasive nanomaterials, as the rapid adsorption of cuticular waxes is no longer mitigated by environmental moisture (Kontogiannatos, Kourti and Mendes, 2020). Concurrently, elevated temperatures can alter the physical state of lipid barriers, potentially increasing the insect cuticle's vulnerability to mechanical abrasion and subsequent desiccation (Ayoub *et al*., 2017). Furthermore, the synergy between these environmental variables and the physicochemical properties of nanomaterials, such as their specific surface reactivity and structural stability, remains essential for optimizing functional responses in pest management(Kamalakannan *et al*., 2025).

8.0 Safety and Environmental Considerations

8.1 Toxicity to Non-Target Organisms

The evaluation of potential ecotoxicological impacts is critical, as the persistence of metal-based nanoparticles in stored commodity ecosystems may inadvertently affect beneficial entomofauna or vertebrate consumers (Vega-Vásquez, Mosier and Irudayaraj, 2020). Concerns regarding their long-term accumulation within the food chain and the potential for unintended disruption of sensitive ecological processes necessitate comprehensive toxicological assessments (Noman *et al*., 2023; Wasule, Shingote and Saxena, 2024). Consequently, future research must prioritize elucidating the molecular mechanisms of particle interactions within mammalian systems to confirm safety profiles and establish standardized regulatory frameworks for food-grade applications (Kumar *et al*., 2021). Moreover, transitioning to intelligent nanosystems with stimuli-responsive release profiles may mitigate these risks by minimizing residual accumulation and environmental imbalance during long-term storage (Yousef *et al*., 2023). Furthermore, addressing the current scarcity of data on the environmental fate of these materials is imperative for developing safer, more environmentally friendly nanopesticide technologies (Yadav *et al*., 2021).

8.2 Environmental Fate and Biodegradation

The current understanding of the degradation pathways of biopolymer-based nanocarriers remains limited, complicating accurate assessment of their long-term behavior in complex storage environments (Lima *et al*., 2021). Comprehensive life-cycle analyses are therefore essential to evaluate how these materials undergo transformation or breakdown, ensuring their mobility does not lead to unwanted persistence within agricultural settings (Prasad, Bhattacharyya and Nguyen, 2017; Zhang *et al*., 2021). Furthermore, the development of advanced analytical techniques is vital to quantify engineered nanoparticles at trace concentrations, as existing methods often fail to characterize their complex dynamics and potential for synergistic effects in environmental compartments (Fraceto *et al*., 2016). Future initiatives must focus on synthesizing environmentally compatible particles that exhibit natural decay, thereby ensuring sustainable remediation without compromising long-term ecological equilibrium (Ghorbani *et al*., 2024). Establishing rigorous regulatory protocols and standardization for the migration and accumulation of these materials is crucial to prevent potential toxicological impacts on human and animal health (Mahato, Mishra and Kumar, 2021; Wypij *et al*., 2023). Furthermore, the formulation of these agents from generally recognized as safe materials, such as specific biopolymers, offers a viable pathway toward enhancing biocompatibility and public acceptance of nano-enabled storage solutions (Lowry *et al*., 2024).

9.0 Challenges and Future Perspectives

9.1 Resistance Development

The potential for insects to develop behavioral or physiological resistance to nanotechnology-based interventions necessitates a proactive strategy, as repeated exposure to uniform mechanical stressors may select for resistant phenotypes over successive generations. To mitigate this risk, future investigations should emphasize developing stimuli-responsive nanoformulations that deliver targeted active ingredients, minimize environmental accumulation, and disrupt pest metabolic pathways (Camara *et al*., 2019; Gupta *et al*., 2023). Additionally, integrating nanoinformatics with existing pest population models can help predict and optimize the long-term effectiveness of these delivery systems under field conditions (An *et al*., 2022). Furthermore, advancing molecular-level studies across diverse animal models is essential for accurately characterizing the mechanisms of action and long-term biological impacts of these nanomaterials (Padmakumar *et al*., 2023). Broadening public awareness and engagement regarding these benefits, potential risks, and safety measures remains a priority to foster the responsible deployment and social acceptance of such emerging technologies (Ram, Kumar and Kumar, 2014; Bratovčić *et al*., 2023).

Ultimately, the successful integration of these innovations relies on harmonizing laboratory-scale findings with stringent regulatory protocols that ensure the safe, sustainable transition of nano-enabled products from research settings to commercial agricultural use (Kah, 2015; Eghbalinejad *et al*., 2024). Integrating green synthesis methods using plant-based or biopolymeric sources can further enhance this transition by minimizing synthetic toxicity and promoting the rapid biodegradation of active agents post-application (Vinzant, Rashid and

Khodakovskaya, 2023; Jabran *et al*., 2024; Raypuriya *et al*., 2025). Moreover, moving beyond conventional synthetic approaches to incorporate biocompatible materials, such as nanochitin, can effectively reduce risks to non-target populations while maintaining robust insecticidal performance (Li *et al*., 2021). Furthermore, the adoption of transdisciplinary research frameworks that bridge gaps among materials science, entomology, and toxicology will be instrumental in addressing current uncertainties regarding the bioavailability and environmental fate of these advanced formulations (Mishra *et al*., 2017; Ghareeb *et al*., 2025).

9.2 Integration with Integrated Pest Management

Integrating nanotechnology into existing Integrated Pest Management programs requires a holistic approach that aligns cultural, physical, and biological control methods with emerging nano-biopesticide innovations (Mawcha *et al*., 2024). Achieving this requires interdisciplinary collaboration among researchers, industry professionals, and policymakers to develop standardized regulatory protocols and foster public confidence in these sustainable delivery systems (Kiruthiga *et al*., 2025). Additionally, comparative cost-benefit analyses of novel nanoformulations versus established commercial products are needed to demonstrate economic viability and encourage adoption within agricultural industries (Campos *et al*., 2018). Establishing robust, transparent management practices and comprehensive education programs for stakeholders is equally vital to ensuring the responsible and safe deployment of these technologies in real-world settings (Páscoli *et al*., 2019; Shekhar *et al*., 2021). Harmonized nanosafety regulatory frameworks that emphasize "safety-by-design" principles will be critical to preventing overutilization of these agents at toxic levels (Mittal *et al*., 2020).

10.0 Conclusion

The integration of nanobiopesticides into storage pest management marks a pivotal step toward sustainable agriculture, leveraging their high selectivity and minimal environmental footprint to overcome the limitations of conventional chemical pesticides. By optimizing the physical and chemical properties of these formulations—such as surface charge and concentration—researchers can significantly enhance the bioavailability of active ingredients while mitigating risks associated with environmental persistence. Furthermore, shifting research toward multifunctional nano-delivery systems that incorporate growth-promoting substances or micronutrients could maximize agricultural output beyond simple pest suppression, thereby providing dual-benefit solutions for food security. However, widespread implementation remains constrained by the scarcity of standardized, eco-friendly bio-nanocarriers and the need to scale up biogenic synthesis processes to achieve commercial viability. To bridge this gap, future efforts must prioritize multi-location field trials to validate the efficacy and scalability of these botanical nanoformulations under diverse real-world conditions.

Acknowledgement

The authors sincerely thank Dr. M. Majeetha Parveen, Head of the Department of Zoology, and the Principal, Government Arts College (Autonomous), Nandanam, Chennai -600035, for providing essential laboratory facilities throughout this work.

References

Abbas, M., Yan, K., Li, J., Zafar, S., Hasnain, Z., Aslam, N., Iqbal, N., Hussain, S.S., Usman, M., Abbas, M. and Tahir, M., 2022. Agri-nanotechnology and tree nanobionics: augmentation in crop yield, biosafety, and biomass accumulation. Frontiers in bioengineering and biotechnology, 10, p.853045.

Abd-Elnabi, A.D. and Badawy, M.E.I. (2024) 'Combating *Spodoptera frugiperda* (*Lepidoptera: Noctuidae*) with Moringa-Synthesized Silica Nanoparticles and Its

Combination with Some Insecticides', Neotropical Entomology, 53(6), pp. 1343–1353. doi:10.1007/s13744-024-01210-0.

Abdou, W.L. *et al.* (2022) 'The insecticidal effect of silica nanoparticles on *Callosobruchus maculates* (*Coleoptera: bruchidae*) and its side effects', Middle East Journal of Applied Sciences [Preprint]. doi:10.36632/mejas/2022.12.3.20.

Adegbola, R.Q. *et al.* (2024) 'Nanobiopesticides in post-harvest management of insect pests of crops: Present status, challenges and prospects – A review', FUDMA Journal of Sciences, 8(4), pp. 40–54. doi:10.33003/fjs-2024-0804-2557.

Agrafioti, P. *et al.* (2020) 'Evaluation of Silica-Coated Insect Proof Nets for the Control of *Aphis fabae*, *Sitophilus oryzae*, and *Tribolium confusum*', Nanomaterials, 10(9), pp. 1658–1658. doi:10.3390/nano10091658.

Ahmad, S. *et al.* (2024) 'Comparative Analysis of Cysteine Protease-based Nano-formulations to Manage *Callosobruchus maculatus Fabricius* and *Trogoderma granarium* Everts in Stored Products', Research Square (Research Square) [Preprint]. doi:10.21203/rs.3.rs-4380927/v1.

An, C., Sun, C., Li, N., Huang, B., Jiang, J., Shen, Y., Wang, C., Zhao, X., Cui, B., Wang, C. and Li, X., 2022. Nanomaterials and nanotechnology for the delivery of agrochemicals: strategies towards sustainable agriculture. Journal of Nanobiotechnology, 20(1), p.11.

Anjana, G., Ahmad, M. and Mir, S.H. (2025) 'Nanotech frontiers: can nanoparticles redefine our approach to insect pest management', Journal of Integrated Pest Management, 16(1). doi:10.1093/jipm/pmaf037.

Ansari, T.H. *et al.* (2025) 'Nanotechnology in Pest Management: Mechanisms, Impacts, and Future Directions for Sustainable Agriculture', Journal of Scientific Research and Reports, 31(4), pp. 589–604. doi:10.9734/jsrr/2025/v31i42983.

Arumugam, G. *et al.* (2015) 'Efficacy of nanostructured silica as a stored pulse protector against the infestation of *bruchid beetle*, *Callosobruchus maculatus* (*Coleoptera*: *Bruchidae*)', Applied Nanoscience, 6(3), pp. 445–450. doi:10.1007/s13204-015-0446-2.

Attia, R.G. *et al.* (2023) 'Cinnamon Oil Encapsulated with Silica Nanoparticles: Chemical Characterization and Evaluation of Insecticidal Activity Against the *Rice Moth*, *Corcyra cephalonica*', Neotropical Entomology [Preprint]. doi:10.1007/s13744-023-01037-1.

Ayilara, M.S. *et al.* (2023) 'Biopesticides as a promising alternative to synthetic pesticides: A case for microbial pesticides, phytopesticides, and nanobiopesticides', Frontiers in Microbiology. Frontiers Media. doi:10.3389/fmicb.2023.1040901.

Ayoub, H.A. *et al.* (2017) 'Synthesis and characterization of silica nanostructures for *cotton leaf worm* control', Journal of nanostructure in chemistry, 7(2), pp. 91–100. doi:10.1007/s40097-017-0229-2.

Baker, S. *et al.* (2017) 'Nanoagroparticles emerging trends and future prospect in modern agriculture system', Environmental Toxicology and Pharmacology. Elsevier BV, pp. 10–17. doi:10.1016/j.etap.2017.04.012.

Baliyarsingh, B. and Pradhan, C.K. (2023) 'Prospects of plant-derived metallic nanopesticides against storage pests - A review', Journal of Agriculture and Food Research, 14, pp. 100687–100687. doi:10.1016/j.jafr.2023.100687.

Bratovčić, A. *et al.* (2023) ‘Application of Nanotechnology in Agroecosystems: Nanoparticles for Improving Agricultural Production’, Reviews in Agricultural Science, 11, pp. 291–309. doi:10.7831/ras.11.0_291.

Camara, M.C. *et al.* (2019) ‘Development of stimuli-responsive nano-based pesticides: emerging opportunities for agriculture’, Journal of Nanobiotechnology. BioMed Central, pp. 100–100. doi:10.1186/s12951-019-0533-8.

Campos, E.V.R., Proença, P.L.F., Oliveira, J.L. de, Melville, C.C., *et al.* (2018) ‘Chitosan nanoparticles functionalized with β-cyclodextrin: a promising carrier for botanical pesticides’, Scientific Reports, 8(1). doi:10.1038/s41598-018-20602-y.

Campos, E.V.R., Proença, P.L.F., Oliveira, J.L. de, Bakshi, M., *et al.* (2018) ‘Use of botanical insecticides for sustainable agriculture: Future perspectives’, Ecological Indicators, 105, pp. 483–495. doi:10.1016/j.ecolind.2018.04.038.

Chhipa, H. (2017) ‘Nanopesticide: Current Status and Future Possibilities’, Agricultural Research & Technology Open Access Journal, 5(1). doi:10.19080/artoaj.2017.05.555651.

Choupanian, M. and Omar, D. (2018) ‘Formulation and physicochemical characterization of neem oil nanoemulsions for control of *Sitophilus oryzae* (L., 1763) (*Coleoptera: Curculionidae*) and *Tribolium castaneum* (Herbst, 1797) (*Coleoptera: Tenebrionidae*)’, Turkish Journal of Entomology, pp. 127–139. doi:10.16970/entoted.398541.

Dantas, J.A. *et al.* (2021) ‘A Comprehensive Review of the Coffee Leaf Miner *Leucoptera coffeella* (*Lepidoptera: Lyonetiidae*)—A Major Pest for the Coffee Crop in Brazil and Others Neotropical Countries’, Insects. Multidisciplinary Digital Publishing Institute, pp. 1130–1130. doi:10.3390/insects12121130.

Deka, B. *et al.* (2021) ‘Nanopesticides: A Systematic Review of Their Prospects With Special Reference to Tea Pest Management’, Frontiers in Nutrition. Frontiers Media. doi:10.3389/fnut.2021.686131.

Devi, G.S. *et al.* (2024) ‘Synthesis, characterization and toxicity assessment of chlorantraniliprole nanoemulsion against *Helicoverpa armigera* (Hubner)’, Research Square (Research Square) [Preprint]. doi:10.21203/rs.3.rs-3958497/v1.

DeVries, J.W., Trucksess, M.W. and Jackson, L.S. (2002) Mycotoxins and Food Safety, Advances in experimental medicine and biology. Springer Nature. doi:10.1007/978-1-4615-0629-4.

Draz, K.A. *et al.* (2023) ‘Assessment of some physical measures as safe and environmentally friendly alternative control agents for some common coleopteran insects in stored wheat products’, Journal of Plant Protection Research [Preprint]. doi:10.24425/jppr.2021.137025.

Eghbalinejad, M. *et al.* (2024) ‘Nano-enabled pesticides: a comprehensive toxicity assessment of tebuconazole nanoformulations with nematodes at single species and community level’, Environmental Sciences Europe, 36(1). doi:10.1186/s12302-024-00879-9.

Elbehery, H.H. *et al.* (2025) ‘Gum Arabic containing Allium sativum L. essential oil-based nanoparticles as biofumigant grain protectant against *Callosobruchus maculatus* F.’, PLoS ONE, 20(10). doi:10.1371/journal.pone.0334926.

Falsini, S. *et al.* (2024) 'Nanoformulations from olive pomace to enhance the efficacy of hydroxytyrosol as a natural pest control agent', Environmental Science Nano, 11(8), pp. 3625–3636. doi:10.1039/d4en00226a.

Fathy, H. (2012) 'Ecosmart Biorational Insecticides: Alternative Insect Control Strategies', in InTech eBooks. doi:10.5772/27852.

Fraceto, L.F. *et al.* (2016) 'Nanotechnology in Agriculture: Which Innovation Potential Does It Have?', Frontiers in Environmental Science, 4. doi:10.3389/fenvs.2016.00020.

Garrido-Miranda, K.A., Giraldo, J.D. and Schoebitz, M. (2022) 'Essential Oils and Their Formulations for the Control of Curculionidae Pests', Frontiers in Agronomy, 4. doi:10.3389/fagro.2022.876687.

Ghareeb, S. *et al.* (2025) 'Current treatments and emerging approaches in stored-product insect pest management', Journal of Stored Products Research, 114, pp. 102745–102745. doi:10.1016/j.jspr.2025.102745.

Ghorbani, A. *et al.* (2024) 'Nano-enabled agrochemicals: mitigating heavy metal toxicity and enhancing crop adaptability for sustainable crop production', Journal of Nanobiotechnology. BioMed Central. doi:10.1186/s12951-024-02371-1.

González, J.O.W. *et al.* (2013) 'Essential oils nanoformulations for stored-product pest control – Characterization and biological properties', Chemosphere, 100, pp. 130–138. doi:10.1016/j.chemosphere.2013.11.056.

Gupta, D. *et al.* (2021) 'Multifunctional activity of graphene oxide-based nanoformulation against the disease vector, Aedes aegypti', Journal of Applied and Natural Science*, 13(4), pp. 1265–1273. doi:10.31018/jans.v13i4.3018.*

Gupta, R. *et al.* (2023) 'Nanopesticides: Promising Future in Sustainable Pest Management', JOURNAL OF ADVANCED APPLIED SCIENTIFIC RESEARCH, 5(2). doi:10.46947/joaasr522023515.

Guru, P.N. *et al.* (2022) 'A comprehensive review on advances in storage pest management: Current scenario and future prospects', Frontiers in Sustainable Food Systems. Frontiers Media. doi:10.3389/fsufs.2022.993341.

Hamel, D., Rozman, V. and Liška, A. (2021) 'Storage of Cereals in Warehouses with or without Pesticides', in Vide Leaf, Hyderabad eBooks. doi:10.37247/paenta.1.22.1.

Haroun, S.A. *et al.* (2023) 'Insecticidal efficiency and safety of zinc oxide and hydrophilic silica nanoparticles against some stored seed insects', Journal of Plant Protection Research [Preprint]. doi:10.24425/jppr.2020.132211.

Helmy, E.A. *et al.* (2022) 'Fungus-synthesized nanoparticles and their target and nontarget effects on stored bean pest beetles and their parasitoid', Research Square (Research Square) [Preprint]. doi:10.21203/rs.3.rs-2097277/v1.

Iavicoli, I. *et al.* (2017) 'Nanotechnology in agriculture: Opportunities, toxicological implications, and occupational risks', Toxicology and Applied Pharmacology. Elsevier BV, pp. 96–111. doi:10.1016/j.taap.2017.05.025.

Ibrahim, S.S. (2019) 'Essential Oil Nanoformulations as a Novel Method for Insect Pest Control in Horticulture', in IntechOpen eBooks. IntechOpen. doi:10.5772/intechopen.80747.

Ibrahim, S.S., Elbehery, H.H. and Samy, A. (2021) 'Insecticidal activity of ZnO NPs synthesized by green method using pomegranate peels extract on stored product insects', Egyptian Journal of Chemistry, p. 0. doi:10.21608/ejchem.2021.92692.4496.

Ibrahim, S.S., Elbehery, H.H. and Samy, A. (2024) 'The efficacy of green silica nanoparticles synthesized from rice straw in the management of *Callosobruchus maculatus* (*Col.*, *Bruchidae*)', Scientific Reports, 14(1). doi:10.1038/s41598-024-58856-4.

Ibrahim, S.S. and Salem, N.Y. (2019) 'Insecticidal efficacy of nano zeolite against *Tribolium confusum* (*Col., Tenebrionidae*) and *Callosobruchus maculatus* (*Col., Bruchidae*)', Bulletin of the National Research Centre/Bulletin of the National Research Center, 43(1). doi:10.1186/s42269-019-0128-4.

Ikawati, S. *et al.* (2020) 'Toxicity nanoinsecticide based on clove essential oil against *Tribolium castaneum* (Herbst)', *Nippon Nōyaku Gakkaishi*, 46(2), pp. 222–228. doi:10.1584/jpestics.d20-059.

Irani, R.Y., Karimpour, Y. and Ziaee, M. (2023) 'Persistence and Efficacy of Two Nanosilica Formulations on *Callosobruchus maculatus* in Different Pulses', Journal of Agricultural Science and Technology, 25(1), pp. 87–98. doi:10.52547/jast.25.1.87.

Jabran, M. *et al.* (2024) 'Exploring the potential of nanomaterials (NMs) as diagnostic tools and disease resistance for crop pathogens', Chemical and Biological Technologies in Agriculture, 11(1). doi:10.1186/s40538-024-00592-y.

Jampílek, J. and Kráľová, K. (2015) 'Application Of Nanotechnology In Agriculture And Food Industry, Its Prospects And Risks', Ecological Chemistry and Engineering S, 22(3), pp. 321–361. doi:10.1515/eces-2015-0018.

Jasrotia, P. *et al.* (2022) 'Nanomaterials for Postharvest Management of Insect Pests: Current State and Future Perspectives', Frontiers in Nanotechnology, 3. doi:10.3389/fnano.2021.811056.

Jayapradha, J. *et al.* (2025) 'Potential nano strategies in insect pest management: synthesis, applications and plant interactions', Plant Science Today [Preprint]. doi:10.14719/pst.7294.

Jesser, E. *et al.* (2020) 'Ecofriendly Approach for the Control of a Common Insect Pest in the Food Industry, Combining Polymeric Nanoparticles and Post-application Temperatures', Journal of Agricultural and Food Chemistry, 68(21), pp. 5951–5958. doi:10.1021/acs.jafc.9b06604.

Jiang, M. *et al.* (2021) 'Phytonanotechnology applications in modern agriculture', Journal of Nanobiotechnology. BioMed Central. doi:10.1186/s12951-021-01176-w.

Kah, M. (2015) 'Nanopesticides and Nanofertilizers: Emerging Contaminants or Opportunities for Risk Mitigation?', Frontiers in Chemistry, 3. doi:10.3389/fchem.2015.00064.

Kah, M. *et al.* (2021) 'Comprehensive framework for human health risk assessment of nanopesticides', Nature Nanotechnology. Nature Portfolio, pp. 955–964. doi:10.1038/s41565-021-00964-7.

Kamalakannan, M. *et al.* (2025) 'Nanotechnology-Driven Solutions for Storage Insect Pest Management: A Solution for Food Security', ACS Agricultural Science & Technology, 5(6), pp. 905–929. doi:10.1021/acsagscitech.5c00128.

Khandehroo, F. *et al.* (2024) 'Enhanced repellent and anti-nutritional activities of polymeric nanoparticles containing essential oils against red flour beetle, *Tribolium castaneum'*, Scientific Reports, 14(1), pp. 18567–18567. doi:10.1038/s41598-024-69318-2.

Khater, H.F., Govindarajan, M. and Benelli, G. (2017) Natural Remedies in the Fight Against Parasites, InTech eBooks. doi:10.5772/63275.

Khorrami, F. *et al.* (2019) 'Cuminum cyminum methanolic extract – Fe3O4 nanocomposite: A novel and efficient insecticide against the potato tuber moth (*Lepidoptera: Gelechiidae*) to protect potatoes', Acta Phytopathologica et Entomologica Hungarica, 54(2), pp. 243–251. doi:10.1556/038.54.2019.018.

Kiruthiga, N. *et al.* (2025) 'Advances in nanocomposite larvicides for mosquito vector management: a comprehensive review', Beni-Suef University Journal of Basic and *Applied Sciences*. Springer Science+Business Media. doi:10.1186/s43088-025-00687-x.

Kontogiannatos, D., Kourti, A. and Mendes, K.F. (2020) Pests, Weeds and Diseases in Agricultural Crop and Animal Husbandry Production, IntechOpen eBooks. IntechOpen. doi:10.5772/intechopen.87515.

Kumar, P. *et al.* (2021) 'Bacillus-based nano-bioformulations for phytopathogens and insect–pest management', Egyptian Journal of Biological Pest Control, 31(1). doi:10.1186/s41938-021-00475-6.

Kumari, R. *et al.* (2023) 'Regulation and safety measures for nanotechnology-based agri-products', Frontiers in Genome Editing. Frontiers Media. doi:10.3389/fgeed.2023.1200987.

Kwenti, T.E. (2017) 'Biological Control of Parasites', in InTech eBooks. doi:10.5772/68012.

Lammari, N. *et al.* (2021) 'Plant oils: From chemical composition to encapsulated form use', International Journal of Pharmaceutics. Elsevier BV, pp. 120538–120538. doi:10.1016/j.ijpharm.2021.120538.

Li, Z. *et al.* (2021) 'Nanochitin whisker enhances insecticidal activity of chemical pesticide for pest insect control and toxicity', Journal of Nanobiotechnology, 19(1). doi:10.1186/s12951-021-00792-w.

Lima, P.H.C. de *et al.* (2021) 'Recent Advances on Lignocellulosic-Based Nanopesticides for Agricultural Applications', Frontiers in Nanotechnology, 3. doi:10.3389/fnano.2021.809329.

Lowry, G.V. *et al.* (2024) 'Towards realizing nano-enabled precision delivery in plants', Nature Nanotechnology. Nature Portfolio, pp. 1255–1269. doi:10.1038/s41565-024-01667-5.

Luneja, R.L. and Mkindi, A.G. (2025) 'Advances in botanical-based nanoformulations for sustainable cotton insect pest management in developing countries', Frontiers in Agronomy, 7. doi:10.3389/fagro.2025.1558395.

Madanayake, N.H., Hossain, A. and Adassooriya, N.M. (2021) 'Nanobiotechnology for agricultural sustainability, and food and environmental safety', Quality Assurance and Safety of Crops & Foods, 13(1), pp. 20–36. doi:10.15586/qas.v13i1.838.

Mahato, D.K., Mishra, A.K. and Kumar, P. (2021) 'Nanoencapsulation for Agri-Food Applications and Associated Health and Environmental Concerns', Frontiers in Nutrition, 8. doi:10.3389/fnut.2021.663229.

Manna, S. *et al.* (2023) 'Current and future prospects of "all-organic" nanoinsecticides for agricultural insect pest management', Frontiers in Nanotechnology, 4. doi:10.3389/fnano.2022.1082128.

Mawcha, K.T. *et al.* (2024) 'Biopesticides for Sustainable Agriculture: A Review of Their Role in Integrated Pest Management', IntechOpen eBooks. IntechOpen. doi:10.5772/intechopen.1006277.

McClements, D.J. *et al.* (2021) 'Nanoemulsion-Based Technologies for Delivering Natural Plant-Based Antimicrobials in Foods', Frontiers in Sustainable Food Systems, 5. doi:10.3389/fsufs.2021.643208.

Mgadi, K. *et al.* (2024) 'Nanoparticle applications in agriculture: overview and response of plant-associated microorganisms', Frontiers in Microbiology, 15. doi:10.3389/fmicb.2024.1354440.

Miksanek, J.R. and Tuda, M. (2023) 'Endosymbiont-mediated resistance to entomotoxic nanoparticles and sex-specific responses in a seed beetle', Journal of Pest Science, 96(3), pp. 1257–1270. doi:10.1007/s10340-023-01596-7.

Mishra, R. *et al.* (2024) 'Innovations and Future Trends in Storage Pest Management', Journal of Experimental Agriculture International, 46(5), pp. 155–165. doi:10.9734/jeai/2024/v46i52366.

Mishra, S. *et al.* (2017) 'Integrated Approach of Agri-nanotechnology: Challenges and Future Trends', Frontiers in Plant Science. Frontiers Media. doi:10.3389/fpls.2017.00471.

Mittal, D. *et al.* (2020) 'Nanoparticle-Based Sustainable Agriculture and Food Science: Recent Advances and Future Outlook', Frontiers in Nanotechnology, 2. doi:10.3389/fnano.2020.579954.

Nawaz, A. *et al.* (2023) 'Nanobiotechnology in crop stress management: an overview of novel applications', Discover Nano. doi:10.1186/s11671-023-03845-1.

Negi, A. and Moses, J.A. (2025) 'Nano-Based Disinfestation Methods for Stored Products', in, pp. 288–312. doi:10.1201/9781003609834-19.

Noman, M. *et al.* (2023) 'Nano-enabled crop resilience against pathogens: potential, mechanisms and strategies', Crop Health, 1(1). doi:10.1007/s44297-023-00015-8.

Omara, A.E.-D. *et al.* (2019) 'Nanoparticles: a Novel Approach for Sustainable Agro-productivity', Environment, Biodiversity and Soil Security, 3(2019), pp. 30–40. doi:10.21608/jenvbs.2019.7478.1050.

Osman, A.I. *et al.* (2024) 'Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review', Environmental Chemistry Letters. Springer Science+Business Media, pp. 841–887. doi:10.1007/s10311-023-01682-3.

Padmakumar, A. *et al.* (2023) 'Bacteria-Premised Nanobiopesticides for the Management of Phytopathogens and Pests', ACS Agricultural Science & Technology, 3(5), pp. 370–388. doi:10.1021/acsagscitech.3c00025.

Páscoli, M. *et al.* (2019) 'Neem oil based nanopesticide as an environmentally-friendly formulation for applications in sustainable agriculture: An ecotoxicological perspective', The Science of The Total Environment, 677, pp. 57–67. doi:10.1016/j.scitotenv.2019.04.345.

Prasad, R., Bhattacharyya, A. and Nguyen, Q.D. (2017) 'Nanotechnology in Sustainable Agriculture: Recent Developments, Challenges, and Perspectives', Frontiers in Microbiology. Frontiers Media. doi:10.3389/fmicb.2017.01014.

Raduw, G.G. and Mohammed, A.A. (2020) 'Insecticidal Efficacy of Three Nanoparticles for the Control of Khapra Beetle (*Trogoderma granarium*) on Different Grains', Journal of Agricultural and Urban Entomology, 36(1), pp. 90–90. doi:10.3954/1523-5475-36.1.90.

Rai, M. *et al.* (2018) 'Copper and copper nanoparticles: role in management of insect-pests and pathogenic microbes', Nanotechnology Reviews, 7(4), pp. 303–315. doi:10.1515/ntrev-2018-0031.

Ram, P., Kumar, V. and Kumar, S. (2014) 'Nanotechnology in sustainable agriculture: Present concerns and future aspects', AFRICAN JOURNAL OF BIOTECHNOLOGY, 13(6), pp. 705–713. doi:10.5897/ajbx2013.13554.

Rankić, I. *et al.* (2021) 'Nano/microparticles in conjunction with microalgae extract as novel insecticides against Mealworm beetles, *Tenebrio molitor'*, Scientific Reports, 11(1). doi:10.1038/s41598-021-96426-0.

Rastogi, A. *et al.* (2019) 'Application of silicon nanoparticles in agriculture', 3 Biotech. Springer Science+Business Media. doi:10.1007/s13205-019-1626-7.

Raypuriya, N. *et al.* (2025) 'Nanotechnology-Based Innovations for Pest Management: A Review', Journal of Advances in Biology & Biotechnology, 28(11), pp. 603–619. doi:10.9734/jabb/2025/v28i113260.

Rouhani, M. *et al.* (2023) 'Synthesis and entomotoxicity assay of zinc and silica nanoparticles against *Sitophilus granarius* (*Coleoptera: Curculionidae*)', Journal of Plant Protection Research [Preprint]. doi:10.24425/jppr.2019.126033.

S, A.A.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). doi:10.1186/s41936-019-0124-0.

Sabbour, M.M. (2019) 'Efficacy of natural oils against the biological activity on *Callosobruchus maculatus* and *Callosobruchus chinensis* (*Coleoptera: Tenebrionidae*)', Bulletin of the National Research Centre/Bulletin of the National Research Center, 43(1). doi:10.1186/s42269-019-0252-1.

Sabbour, M.M. (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/Bulletin of the National Research Center, 44(1). doi:10.1186/s42269-020-00336-6.

Sabbour, M.M. and El-Aziz, S.E.A. (2019) 'Impact of certain nano oils against *Ephestia kuehniella* and *Ephestia cutella* (*Lepidoptera-Pyralidae*) under laboratory and store conditions', Bulletin of the National Research Centre/Bulletin of the National Research Center, 43(1). doi:10.1186/s42269-019-0129-3.

Sabuncuoğlu, S. (2019) Mycotoxins and Food Safety, IntechOpen eBooks. IntechOpen. doi:10.5772/intechopen.77743.

Salem, A. (2020) 'Comparative Insecticidal Activity of Three Forms of Silica Nanoparticles on some Main Stored Product Insects', Journal of Plant Protection and Pathology

/Journal of Plant Protection and Pathology, 11(4), pp. 225–230. doi:10.21608/jppp.2020.96009.

Salem, A., Hamzah, A. and El-Taweelah, N. (2015) 'ALUMINUM AND ZINC OXIDES NANOPARTICLES AS A NEW METHODS FOR CONTROLLING THE RED FLOUR BEETLES, *Tribolium castaneum* (HERBEST) COMPARED TO MALATHION INSECTICIDE.', Journal of Plant Protection and Pathology /Journal of Plant Protection and Pathology, 6(1), pp. 129–137. doi:10.21608/jppp.2015.53186.

Sayed, T.S.E., Rizk, S.A. and Sayed, R.M. (2023) 'Cellophane packaging treated with nano silica is superior to polyethylene in reducing stored irradiated flour from *Tribolium confusum* infestation', International Journal of Tropical Insect Science, 43(6), pp. 2121–2127. doi:10.1007/s42690-023-01111-6.

Shahid, A., Faizan, M. and Raza, M.A. (2023) 'POTENTIAL ROLE OF SILVER NANOPARTICLES (AgNPs) AND ZINC NANOPARTICLES (ZnNPs) FOR PLANT DISEASE MANAGEMENT', Agrobiological Records, 14, pp. 59–69. doi:10.47278/journal.abr/2023.039.

Shahid, M. *et al.* (2023) 'BIOPESTICIDES: A POTENTIAL SOLUTION FOR THE MANAGEMENT OF INSECT PESTS', Agrobiological Records, 13, pp. 7–15. doi:10.47278/journal.abr/2023.022.

Shangguan, W. *et al.* (2024) 'Making the Complicated Simple: A Minimizing Carrier Strategy on Innovative Nanopesticides', Nano-Micro Letters. Springer Science+Business Media. doi:10.1007/s40820-024-01413-5.

Shekhar, S. *et al.* (2021) 'The framework of nanopesticides: a paradigm in biodiversity', Materials Advances, 2(20), pp. 6569–6588. doi:10.1039/d1ma00329a.

Shelar, A. *et al.* (2023) 'Recent Advances in Nano-Enabled Seed Treatment Strategies for Sustainable Agriculture: Challenges, Risk Assessment, and Future Perspectives', Nano-Micro Letters. Springer Science+Business Media. doi:10.1007/s40820-023-01025-5.

Shoaib, A. *et al.* (2018) 'Preparation and characterization of emamectin benzoate nanoformulations based on colloidal delivery systems and use in controlling Plutella xylostella (L.) (*Lepidoptera: Plutellidae*)', RSC Advances, 8(28), pp. 15687–15697. doi:10.1039/c8ra01913d.

Singh, A. *et al.* (2023) 'Revolutionizing Crop Production: Nanoscale Wonders - Current Applications, Advances, and Future Frontiers', Egyptian Journal of Soil Science, 64(1), p. 0. doi:10.21608/ejss.2023.246354.1684.

Singh, A. *et al.* (2024) 'Nanotechnology Products in Agriculture and Environmental Protection: Advances and Challenges', Egyptian Journal of Soil Science, 64(4), p. 0. doi:10.21608/ejss.2024.300047.1802.

Sohrabi, F. *et al.* (2024) 'Insecticidal efficacy of synthesized ZnO nanoparticles using brown algae *Cystoseira baccata* extract against *Callosobruchus Maculatus* (F.) (*Col.: Chrysomelidae*)', Research Square (Research Square) [Preprint]. doi:10.21203/rs.3.rs-3834522/v1.

Stadler, T. *et al.* (2011) 'Comparative toxicity of nanostructured alumina and a commercial inert dust for *Sitophilus oryzae* (L.) and *Rhyzopertha dominica* (F.) at varying ambient humidity levels', Journal of Stored Products Research, 48, pp. 81–90. doi:10.1016/j.jspr.2011.09.004.

Thabet, A.F. *et al.* (2021) 'Silica nanoparticles as pesticide against insects of different feeding types and their non-target attraction of predators', Scientific Reports, 11(1). doi:10.1038/s41598-021-93518-9.

Vega-Vásquez, P., Mosier, N.S. and Irudayaraj, J. (2020) 'Nanoscale Drug Delivery Systems: From Medicine to Agriculture', Frontiers in Bioengineering and Biotechnology. Frontiers Media. doi:10.3389/fbioe.2020.00079.

Vinzant, K., Rashid, M.M. and Khodakovskaya, M.V. (2023) 'Advanced applications of sustainable and biological nano-polymers in agricultural production', Frontiers in Plant Science. Frontiers Media. doi:10.3389/fpls.2022.1081165.

Wang, D. *et al.* (2022) 'Nano-enabled pesticides for sustainable agriculture and global food security', Nature Nanotechnology, 17(4), pp. 347–360. doi:10.1038/s41565-022-01082-8.

Wasule, D.L., Shingote, P.R. and Saxena, S. (2024) 'Exploitation of functionalized green nanomaterials for plant disease management', Discover Nano. doi:10.1186/s11671-024-04063-z.

Whyte, R.O. and Shand, R.T. (1970) 'Agricultural Development in Asia', Geographical Review, 60(4), pp. 592–592. doi:10.2307/213785.

Wypij, M. *et al.* (2023) 'The strategic applications of natural polymer nanocomposites in food packaging and agriculture: Chances, challenges, and consumers' perception', Frontiers in Chemistry. Frontiers Media. doi:10.3389/fchem.2022.1106230.

Xu, L. *et al.* (2010) 'Applications and toxicological issues surrounding nanotechnology in the food industry', Pure and Applied Chemistry, 82(2), pp. 349–372. doi:10.1351/pac-con-09-05-09.

Yadav, J. *et al.* (2021) 'Nanopesticides: Current status and scope for their application in agriculture', Plant Protection Science, 58(1), pp. 1–17. doi:10.17221/102/2020-pps.

Yousef, H.A. *et al.* (2023) 'Nanotechnology in pest management: advantages, applications, and challenges', International Journal of Tropical Insect Science, 43(5), pp. 1387–1399. doi:10.1007/s42690-023-01053-z.

Zhang, P. *et al.* (2021) 'Nanotechnology and artificial intelligence to enable sustainable and precision agriculture', Nature Plants. Nature Portfolio, pp. 864–876. doi:10.1038/s41477-021-00946-6.

Zhao, X. *et al.* (2017) 'Development Strategies and Prospects of Nano-based Smart Pesticide Formulation', Journal of Agricultural and Food Chemistry, 66(26), pp. 6504–6512. doi:10.1021/acs.jafc.7b02004.

Ziaee, M., Takabi, A.S. and Ebadollahi, A. (2023) 'Fabrication of *Carum copticum* essential oil–loaded chitosan nanoparticles and evaluation its insecticidal activity for controlling *Rhyzopertha dominica* and *Tribolium confusum*', Frontiers in Plant Science, 14. doi:10.3389/fpls.2023.1187616.

Ziaee, M. and Zahra, G. (2016) 'Insecticidal efficacy of silica nanoparticles against *Rhyzopertha dominica* F. and *Tribolium confusum Jacquelin du Val'*, Journal of Plant Protection Research, 56(3), pp. 250–256. doi:10.1515/jppr-2016-0037.