Review Article

Role of Nanoparticles in Stored-Product Insect Pest Management: A Review

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Abstract | Currently, nanotechnology has provided numerous solutions to the problems of using chemical pesticides, especially in controlling insect pests of stored, because of its specifications that make it promising in the field of controlling insect pests. One of the most important specifications that characterize nano-insecticides is the small size of their particles and increased surface area, as well as the range of shapes they can take, including nano emulsions, nanocapsules, nano suspensions, etc. Soon, it is anticipated that nanopesticides will transition from the research stage to practical application and production field due to the accelerating pace in the amount of research in this specialty. Support for this viewpoint comes from the diversity of methods for synthesizing nanoparticles, which include chemical, physical, and biological methods. This review highlights a wide range of tested nanoparticles, such as silver nanoparticles, gold nanoparticles, silica nanoparticles, and others, which have been applied to a wide range of stored product insect pests, including *Tribolium castaneum*, *Sitophilus oryzae* and *Callosobruchus maculatus* among others. Despite their promise, nanopesticides require further evaluation, especially in their impact on health, the environment, and the fate of these nanoparticles after treatment, so that they do not face the same failures that have occurred with chemical pesticides.

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Introduction

The rapid pace of development in many fields of science led to searches for new applications of those sciences. At this time, the selection of nanomaterials as one of the most promising applications in the field of scientific and applied research. Agricultural sciences had the largest share of the application of nanoparticles in the agricultural field, which were used in two main fields: Nanofertilizers and nanopesticides (Nongbet *et al*., 2022; Mohmed, 2020). After the recorded damage of chemical pesticides to humans, the environment, and animals, nanopesticides came as one of the potential alternatives, which have taken up a large space in the research field recently because they possess many qualities Including small size (1-100) nm and increased surface area (Dimetry and Hussein, 2016). Nanopesticides also reach plants using controlled delivery systems compared with traditional chemical pesticide formulations, where more than 90% of conventional pesticides leak into the environment and cause damage to it. Efficiency is increased by the controlled delivery system's ability to prolong the active ingredient's release at the target site for a longer amount of time, thus increasing efficiency in targeting their targets, such as plants, insects and, pathogens (John *et al*., 2017). Nanopesticides are also characterized by increased resistance to photodegradation in the environment compared to traditional chemical pesticides by preserving the active substance from sunlight, especially ultraviolet rays, which makes their effect on the plant for a longer period and thus has a longer effect, which reduces the number of times they are used compared to traditional pesticides (Chand *et al*., 2017). In addition to the presence of nanopesticides in multiple forms as nanocapsules, nanosuspension, nanoemulsion, nanospheres (Nuruzzaman *et al*., 2016). In addition, it has not been proven that pests have shown resistance to nanopesticides (Yin *et al*., 2023). The diversity of nanoparticle synthesis processes (chemical, physical, and biological) has given impetus to the manufacturing and spreading nanopesticides. Biosynthesis, or what is known as green synthesis, is considered one of the most important types of synthesis of nanoparticles, relying on plant extracts (Hasoon *et al*., 2023) or secondary metabolic compounds of fungi (Jabbar *et al*., 2023) as reducing agents in the process of synthesis of nanoparticles. Many research and review articles in the field of storage pests have addressed the importance of nano pesticides in control of these pests (Jasrotia *et al*., 2022). However, more studies and other research must be conducted in this field to know the effect of different types of nanoparticles on the life performance of many insect species. Therefore, this review comes to document many of the research and manuscripts that includes the effect of different types of nanoparticles on many stored insect pests.

Materials and Methods

Tribolium castaneum

Tribolium castaneum (Herbst) belongs to the (Tenebrionidae: Coleoptera) It is considered one of the most important global secondary insect pests that affect stored grains and other food products (Richards *et al*., 2008). Many nanoparticles have been tested as potential nanoinsecticides against this pest, where different concentration levels of SiNPs and AgNPs were tested to assess their effects on *T. castaneum* mortality by using the feeding method, The result revealed that AgNPs recorded 40% mortality, while SiNPs recorded 70% mortality and These results found that the synthesized SiNPs have a greater potential as an alternative option in managing pests in stored products compared to AgNPs at the same exposure time (four days) (Salah *et al*., 2023). Al-Fatlawy and AL-Zurfi (2023) evaluated three types of nanoparticals, aluminium oxide (ANPs), zinc oxide (ZNPs) and nanoparticles silicon oxide (SNPs) on the second fifth-instar larvae and adults of *T. castaneum* (Herb.) with many different concentrations and the results of their study showed that SNPs and ANPs were significantly more effective than ZNPs at all tested concentrations after 15 days post-treatment. as well as the effect of nanoparticles silicon oxide (SNPs) on the fecundity of *T. castaneum*. The high concentration of TiO2 and ZnO nanoparticles recorded high cumulative mortality of the adult insect *T. castaneum* after exposure times 1, 3, and 5 days from treatments (Hilal *et al*., 2021). Abd-El-Salam *et al*. (2015) Two nanoparticles, aluminum oxide (Al2O3) and zinc oxide (ZnO) were used as stored product protectants against infestation of insect *T. castaneum* compared to chemical insect malathion as a standard reference, Results accentuated that the two nanoparticles (Al2O3 and ZnO) significantly inhibited the number of progeny and weight loss (%). Also, ZnO had the most effect compared to Al2O3 nanoparticles. Three nano-particles nano-malathion, organic nano-silica and inorganic nano-silica were teasted by mixing with grains under laboratory conditions against the adults of *T. castaneum* (Herbst). The results showed the highest adverse effect on all parameters appeared after 14 days of treatment. Also, Inorganic nano silica showed a significant inhibitor on the number of *T. castaneum* adult progeny at the lower concentration (Khalil *et al*., 2019). Copper nanoparticles biosynthesis by using two plant extracts (*Acacia cornigera* and *Annona purpurea*) evaluated against *T. castaneum*, where the copper nanoparticles from *A. cornigera* showed effective insecticidal activity against *T. castaneum* and the mortality recorded at 90% compared with 76.6% obtained from copper nanoparticles of *A. purpurea* (Solorzano-Toala *et al*., 2024). Alif and Thangapandiyan (2019) studied the silver nanoparticles synthesized and tested against *T. castaneum* to compare the insecticidal efficacy of nanoparticles with commercial insecticide malathion, The study was conducted to compare the mortality rate, ovipositional deterrent, repellent activity, and antifeedent activity of different concentrations of malathion, silver nanoparticles, and the mixed suspension of silver nanoparticles and malathion against *T. castaneum*. The results of all the assays clearly showed that the combination of silver nanoparticles with malathion shows high insecticidal efficacy.

Callosobruchus maculatus

Callosobruchus maculatus (Fabricius) (Coleoptera: Bruchidae) is an agricultural insect that lives in tropical and subtropical regions of the world, it is the most detrimental to cowpeas, reducing output by more than 90%. It infests legumes that have been stored, especially those in the genus Vigna, by reducing the quality and quantity of stored grains where the larvae feed and develop inside the legumes (Fabaceae) seed (Beck and Blumer, 2014). Because of its economic importance, the insect has taken an important role among researchers, as many nanoparticles have been evaluated for its control, Lakshmi *et al.* (2020) studied the effect of zinc oxide nanoparticles at different concentrations on pulse beetle *C. maculatus* in greengram in terms of different entomological parameters, namely, adult mortality and number of eggs, where the highest mortality was recorded at 100% on the 14th day from treatment, while the number of eggs per 100 seeds was lower in the same treatment (13.33), and the highest was recorded in control with 27.33 eggs/100 seeds. Helmy *et al.* (2023) recorded reduced hatchability and reduced larva-to-adult of *C. chinensis* and *C. maculatus* When treated withsix types of nanoparticles (NPs) using extracts from the fungus *Fusarium solani*: Silver (AgNPs), selenium (SeNPs), silicon dioxide (SiO2NPs), copper oxide (CuONPs), titanium dioxide (TiO2NPs) and zinc oxide (ZnONPs) ranging in size from 8 to 33 nm. Rouhani *et al.* (2013) found the effectiveness of silica nanoparticles (SNP) and silver nanoparticles (AgNP) on larval stage and adults of *C. maculatus* on cowpea seed, The results showed that both nanoparticles (silica and silver) were highly effective against adults and larvae, with 100% and 83% mortality, respectively. Arumugam *et al.* (2016) tested the protection of five pulse seeds types from the infestation by stored pulse beetles, *C. maculatus*, by treating pluse seeds with hydrophobic silica nanoparticles (SNPs) with the pulse seeds, where the results revealed a significant reduction in oviposition and adult emergence, and there was a complete retardation of growth of this beetle in the treated seeds of these six varieties of pulses. Yerragopu *et al.* (2019) mentioned the effect of plant-mediated synthesized silver nanoparticles using curry leaves on pulse beetle *C. chinensis*, where recorded adult mortality of 100% was observed on the 7th day after treatment. Rahman *et al.* (2020) stated that nickel-oxide nanoparticles (NiO NPs) synthesized by aqueous leaf extract of *Rauvolfia serpentine* has been tested on *C. maculatus* in a dose-dependent manner, the *C. maculatus* on black gram seeds treated with 5, 10, 20, and 40 ppm NiO NPs showed reduced fecundity and an extended developmental time.

Sitophilus oryzae

The rice weevil, *Sitophilus oryzae* L. (Coleoptera: Curculionidae), is a major and destructive pest of stored cereal grains, including rice, wheat, barley, and maize. Most cereal-producing countries are home to this insect pest; both larvae and adults severely damage the grain and cause weight losses due to their internal and external feeding, in addition to its extended period of development, great fecundity, and overlapping generations (Nwaubani *et al.*, 2014). Many studies have been conducted to test different types of nanoparticles that were synthesized from different sources and were biologically tested on this insect pest. A high mortality was caused when zinc nanoparticles were applied to the larval stage and adults of *S. granarius* two weeks after treatment (Rouhani *et al.*, 2019). Ismail *et al.* (2021) indicated that while zinc nanoparticles (ZnO) had a mildly beneficial effect on *S. oryzae*, aluminum nanoparticles (Al2O3) were far more effective with exposure time and concentration level. increased, so did insect death (%). Also, the two materials considerably reduced the number of progeny. Sabbour (2012) evaluated two types of nanoparticles alaminium oxide (Al2O3) and titanium dioxide (TiO2) that were tested as nanopesticides against rice weevil *S. oryzae* under laboratory and store conditions, The results indicated that nano TiO2 was only moderately effective against *S. oryzae* while nano Al2O3 was shown to be very efficient against *S. oryzae*. Sabbour (2015) recorded the number of eggs laid/female significantly reduced *S. oryzae* when treated with Nanoparticle 4 silica gel Cab-O-Sil-750 and silica gel Cab-O-Sil-500 and increased in the mortality rate of *S. oryzae.* In addition to reduction values in the number of laid eggs and adult emergence of *S. oryzae*. Patil *et al.* (2019) teasted the efficacy of amorphous rice husk silica nanoparticles against *S. oryzae* and *Xanthomonas oryzae.* It was observed that adult mortality of *S. oryzae* depends on dose and time after application, and the adult mortality on the 4th days showed a significant mortality rate of

100% of *S. oryzae* with negligible weight loss. Sankar and Abideen (2015) tested the Insecticidal effect of aqueous extract and synthesized silver nanoparticles of *Avicinia marina* against the adults of *S. oryzae* where complete mortality (100%) was observed over 4 days with 10 *S. oryzae* in the experiment. Zahir *et al.* (2012) found the effect of silver nanoparticles (Ag NPs) was synthesized by using aqueous leaf extracts of *Euphorbia prostrata* against the adults of *S. oryzae* L. where the results suggest that the synthesized Ag NPs have the potential to be used as an ideal eco-friendly approach for controlling *S. oryzae*. The insecticidal activity of the nanoemulsions prepared by castor oil (*Ricinus communis*) against the insect rice weevil *S. oryzae* L. was evaluated in the laboratory using a contact toxicity bioassay. It was found that the adult mortality percentage increased with dose and time, and it gave protection from emerging adults of *S. oryzae* to the wheat grains until the 3 month storage period (Abd El-Naby *et al.*, 2020). *Mentha piperita* nano-emulsion demonstrated high adult insect mortality at low doses when tested against the rice weevil, *S. oryzae* Furthermore, increased exposure time and concentration led to increased mortality of *S. oryzae*, Significant variations in adult emergence in *M.piperita* nano-emulsion were also observed in the data following a 6-week treatment period (Massoud *et al.*, 2018). The efficacy, stability, and usage of *Pelargonium graveolens* essential oil was assessed with its nano-formulation and its impact on *S. oryzae* L. According to the results of the bioassays, the *P. graveolens* nanoemulsion aexhibited a lower LC50 value of 2.298 ppm/cm2, indicating a higher level of toxicity. Moreover, adult mortality increased with longer exposure intervals. Six weeks after exposure to this beetle, the emergence of progeny was generally low and decreased further with increasing concentrations over a three-month period (Mesbah *et al.*, 2023).

Mode of action nanopesticides

The effect of nanoparticles on stored-product insects depends on the type of particles, the method of their synthesis, and the targeted insects species and life stages. Conditions nanoparticle preparation, such as temperature, pH, reaction time, and type of reducing agent, significantly influence the synthesis process and the stability of the nanoparticles. These factors enhance the nanoparticles' properties, reducing their size and increasing their interaction surface with the insect's body, thereby amplifying and prolonging their effectiveness (Ali *et al.*, 2024). A limited number of studies have been conducted to investigate the mode of action of various nanoparticles on certain stored-product. insects. whether they are coated or uncoated, and the different exposure times and methods. Additionally, their effects can vary based on whether they act on the insect's external surface or enter the digestive system through ingestion, leading to outcomes such as DNA damage, enzyme denaturation, and other physiological disruptions. (Jiang *et al.*, 2015). Some studies have highlighted the intestinal effects of nanoparticles when with food, leading to their entry into the digestive tract, and causing insect mortality dueto impairment of the digestive system (Smith, 1969). The respiratory system and obstruction of the trachea and spiracle due to the effect of nanoparticles had another role and cause of the death of stored insects (Keratum *et al.*, 2015). The high mortality rate also occurs due to desiccation-induced disruption of mating behavior and high temperatures because the use of nanoparticles (Salem, 2020). However, the physical effects of nanoparticles remains the most significant, These particles damage the protective wax layer of the insect cuticle through sorption or abrasion, causing water loss, dehydration, and ultimately death (Arumugam *et al.*, 2016). Some insects were killed solely by physical methods, as silica nanoparticles disrupted the protective barrier of the cuticular lipids through physio-sorption (Barik *et al.*, 2008). Silica nanoparticles exhibit significant insecticidal potential, by absorbing the insect wax layer, which leads desiccation and, to a lesser extent, abrasion futher exacerbating cuticle desiccation and causing insect death (Masumeh and Zahra, 2016). Like most nanoparticles, silver nanoparticles (Ag NPs) can penetrate the larval membrane, leading to various pathophysiological anomalies that ultimately cause the insect's death, additionally AgNPs can block copper entry into cells, causing a copper deficit, which makes them poisonous to insects. There is another effect of copper where it reduces the activity of enzymes and the production of proteins within the cell (Armstrong *et al.*, 2013). Copper nanoparticles (Cu-NPs) can easily cross endothelial and epithelial cells and via transcytosis, reducing the activity of acetylcholinesterase (AChE), which is the cause of their poisonous impact. Moreover, they play a part in oxidative stress since they may move across insects' lymphatic vessels, axons, and dendrites with ease (Avis-Tresa and Antony, 2019; Shahzad and Manzoor, 2019; Weldegebrieal, 2020). Furthermore, successful mating in certain insects relies on the greasy layer on females' bodies, which serves as an attachment point for male beetle feet. The drying effect of nickel oxide nanoparticles (NiO-NPs) on female insects may have reduced oviposition and mating rates (Rahman *et al*., 2020).

Conclusions and Recommendations

Many challenges, including environmental issues, insect pests and other problems affecting agricultural production and food security, have driven scientific researches to seek appropriate solutions. One of the latest advancments is nanotechnology, which has been applied in agriculture through two main approaches: nanofertilizers and nanopesticides, aiming plant health and increase productivity. Stored-product pests represent one of the most important challenges in the post-harvest stage, due to the speed of their reproduction, the diversity of their damage, the hosts they infect, and the environmental conditions in which they are found. This is why it is of great importance in the field of using nanotechnology to control it, Despite the lack of studies and research regarding it, it is constantly increasing because of the preliminary results shown by various types of nanoparticles in controlling them. Especially with the lack of resistance to it by stored pests and the limited quantity used due to its small size with an increase in effect. With the increase in research in this field, scientists are focusing on natural methods for nanoparticle preparation, known as, biosynthesis or green synthesis, due to potential risks associated with synthetic nanoparticles.

Currently, no laws or regulations govern their mechanism of action, usage, or distribution, leaving a significant task for researchers to know the fate of these nanoparticles and the effect of their residues, In addition to finding new structures for these nanoparticles that increase their efficiency, provide stability, and ensure their rapid delivery to intended targets.

Novelty Statement

The manuscript's most important novelty is that it addresses the topic of nanopesticides, which are considered one of the most recent methods of control and includes the most recent studies in this field.

Conflict of interest

The authors have declared no conflict of interest.

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