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NANOBIOPESTICIDES IN POST-HARVEST MANAGEMENT OF INSECT PESTS OF CROPS: PRESENT STATUS, CHALLENGES AND PROSPECTS – A REVIEW

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ABSTRACT
The major universal challenge on our planet is the issue of establishing food security for a rapidly increasing population in the world. Farmers all over the world focus on using new innovations and technologies for enhancing the production and storage of crops through intensive and extensive agriculture. The current efforts lead to the formation of nanopesticides and nanobiopesticides (NBPs) which has been made possible by advances in nanotechnology. Nanotechnology is one of the promising areas to boost the availability of food and to manufacture newer products for beneficial purposes in agriculture, food, water, the environment, medicine, energy, and electronics.NBPs are made using a variety of surfactants, polymers, nanoemulsions, nanocapsules, and metal nanoparticles with sizes in the nanometer range. These NBPs with an elevated surface-to-volume ratio are able to target organisms more effectively and persistently than traditional pesticides because of their physical characteristics and may continue to be effective for longer periods of time. In comparison to conventional pesticides, NBPs have the potential to improve the environment by decreasing toxicity, extending the shelf life of agricultural produce with the aid of nanoparticles, and enhancing the solubility of pesticides that are poorly soluble in water. However, the commercialization of NBPs faces significant obstacles due to their applicability in real-world settings, legal compliance, and market acceptability. Enhancing the usage and spread of NBPs are beneficial in reducing the number of spread chemicals, minimize nutrient losses in fertilization, and increased yield through pest and nutrient management.

Keywords: Delivery system, Eco-friendly, Micro-organism, Nanotechnology, Nanometer, Sustainability

INTRODUCTION

The world's population is expected to reach nine (9) billion by the year 2050 according to projection by United Nations when, food demand expected to increase from 59 to 98% (Duro *et al*., 2020). This calls for a holistic approach involving judicious use of resources for increased cultivation, sustainability and post harvest management of crops. Hence, it will lead to food and nutritional security for the teeming population. However, agricultural production confronts several challenges such as improvement of nutritional content, enhancement of the crop yield, and prevention of food loss. Time and again, the postharvest crop losses can exceed the losses that crops suffer in the field, because climatic and biotic factors like pests have a major play in food loss during post-harvest periods. The direct availability of nutrients (protein, carbohydrates, fats, vitamins, mineral and oils) for the insects in the stored grains like cereals, pulses and oilseeds, makes it an easier target for the storage pests (Sarwar *et al*., 2013; Oso and Ashafa, 2021).The economic value and human consumption of these grains are greatly diminished as a result of these insect infestations (Sharon *et al.*, 2014; Wang *et al*., 2021).

Insects in stored grains are controlled using various approaches, including mechanical, chemical, biological, and physical methods. However, fumigation is the most widely used approach because it can be applied to a variety of storage levels and environments, including mills, silos, bags, and warehouses (Nguyen *et al*., 2015; Nayak *et al*., 2020). Synthetic pesticides play a pivotal role in enhancing food production through control against harmful insect pests and they are readily available in the market with low labour and effort (Nafiu and Ibrahim 2021). They are the most widely used approach in controlling stored insect pests; varying level of success have been achieved using synthetic pesticides, however, high cost , ineffectiveness due to antimicrobial resistance , toxicity, and obsolete while in stock due to poor logistics and delays in receiving them at the point of need made them detrimental to both human health and the environment. These have made synthetic pesticides a source of concern leading to calls for innovative approach (Jallow *et al*., 2017; Poudel *et al*., 2020; Nafiu and Ibrahim 2021).

Globally, farmers are generally focused on applying new discoveries and technologies to improve food output and storage through vast and intensive farming practices (Ashraf *et al*., 2021).

One promising field that could increase food availability and produce new products for use in agriculture, food, water, the environment, medicine, energy, and electronics is nanotechnology. According to Sadeghi *et al*. (2017), this area is rapidly evolving and has unique uses in food research and agriculture. Nanotechnology is regarded as a highly attractive tool to achieve the goal of lowering the quantity of pesticide used in the current agricultural environment, where major challenges include environmental contamination, pest resistance, bioaccumulation, and health hazards. These novel active ingredients, together with new methods for the formulation and delivery of pesticide active ingredients, are collectively referred to as nanobiopesticides (Hayles *et al*., 2017; Shukla *et al*., 2019). The main advantage of the use of NBPs is the reduction in quantity of pesticide needed before and after harvest of crops and processed commodities. It has been shown that nanotechnology, which works with materials at the nano-scale, has a lot of promise for developing cutting-edge pest control methods (Kashyap *et al*., 2016; Unsworth *et al*., 2016; Kashyap *et al*., 2020). By increasing the efficacy of pesticides, stabilizing their active ingredients, reducing dosage requirements, and conserving agricultural inputs, nanotechnology will help solve the drawbacks of conventional pesticides (Jasrotia *et al*., 2018; Rikta and Rajiv, 2021).

Foods of exceptional quality can be produced in a much more improved and practical form, with increased nutrient bioavailability using nanotechnology. Abobatta (2018), Axelos and Van De Voorde (2017), Dasgupta *et al*. (2015), Peters *et al*. (2016), and other research studies are emphasizing the growing application of nanotechnology for agricultural production and food processing. The principles, mode of action, applications for reducing postharvest loss, and function of NBPs in promoting food security are all covered in this review, along with the challenges and potential applications in ensuring food and nutritional security in agricultural and allied systems.

Nanobiopesticides (NBPs)

NBPs are biological protection products that are created with nanotechnology to improve efficacy and lower the amount of pesticides in the environment (Chaudhary *et al*., 2021b–2021d).They are small formulations that are highly effective at controlling pests while having less residual toxicity and being environmentally friendly. NBPs are two- or three-dimensional nanostructures that are used to transport the contents of agricultural pesticides. They can also assist make the ingredients more bio-available and soluble in water, as well as shield the chemicals from deterioration caused by the environment, and as a result, insect, weed, and pathogen control in crops are also revolutionized by it (Yadav *et al.*, 2020). NBPs are applied specifically fixed on a hybrid substrate, encapsulated in functionalized nanocarriers for triggers mediated by enzymes or external stimuli (Agostini *et al*., 2012; Khati *et al*., 2018; Kumari *et al*., 2020; Agri *et al.*, 2021, 2022; Chaudhary *et al*., 2022; Pan *et al*., 2023). NBPs occur in different of forms, including nano-gel, nano-encapsulation, nano-fibres, and nano-sphere/microsphere (Rajna &Paschapur 2019; Pan *et al*. 2023).

Classes of Nanoparticles for the Formulation of Nanobiopesticide

Three categories were established for nanoparticles based on their size:

i. Particles that are ultrafine and have a diameter of less than 100 nm;
ii. Particles that are accumulation-mode and have diameter between 100 nm and 2.5 µm; and 3) Particles that are coarse-mode and have a diameter larger than 2.5 µm (Sioutas *et al*., 2005; Kah *et al.,* 2013; Kashyap *et al.,* 2017; Kashyap *et al*., 2018; Yadav *et a*l., 2021).

Furthermore, in harmony with their chemical composition, nanoparticles can be further divided into three main groups:

i. Organic-based biodegradable nanoparticles (liposomes, solid lipids, and polymeric nanoparticles);
ii. Inorganic-based, solid, and non-biodegradable nanoparticles (gold, silver, copper, iron, and silica-based nanoparticles); and
iii. Hybrid nanoparticles (combination of both inorganic and organic components), as shown in Figure 1. Inorganic-based NBPs have undergone more testing for the reduction of storage insect pests in comparison to other categories (Goodsell 2004).

Additionally, when compared to chemical-based NBPs, plant-based nanoparticles have garnered increased attention for the management of stored grain pests since they are easy to manufacture and harmless for the environment (Goodsell 2004; Chen *et al*., 2019). The microorganisms or their bioactive chemicals can be used to create nanomaterials (Kashyap *et al*., 2018; Bazana *et al*., 2019). Figure 1 shows the types of nanoparticles based on their sizes and chemical composition.

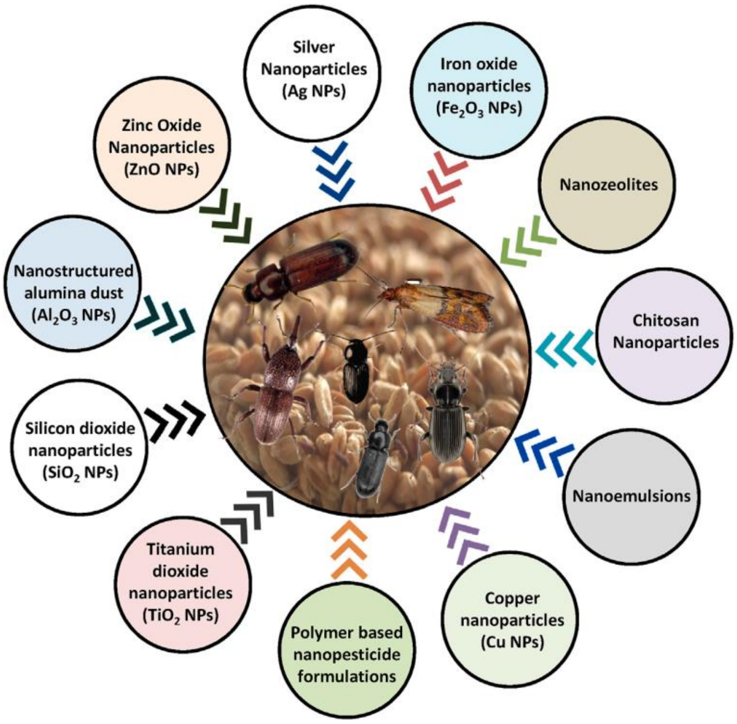

Figure 1: Types of prospective nanomaterials and nanoformulations suggested for insect pest management under storage. Source: Jasrotia *et al.*, (2022)

Major groups of Nanobiopesticides (NBPs)

NBPs are nanoparticles produced from biological agents which are environmental-friendly, specific in their mode of action, sustainable, do not leave residues, and are not associated with the release of greenhouse gases (Borges *et al*., 2021; Abdollahdokht *et al*., 2022). They can be grouped into two (2) categories namely; based on the target organism and also based on delivery system. These groups of NBPs necessitate effective delivery of nano formulations on the target organisms.

Based on the target organism

The nano-formulations of biopesticides are named according to target organisms, i.e., herbicides (against parasitic weeds), insecticides (against insects), acaricides (against mites), molluscicides (against snails/slugs), rodenticides (against rodents), bactericides, and fungicides, just as conventional pesticides are classified according to their targets of pests (Yadav & Devi, 2017). Due to their diversity and many bioactive components, plants are a desirable source for the development of insecticidal chemicals. The presence of different bioactive compounds including phytopesticides with myriad of phytochemical compounds in plants helps in understanding of the development and formulation of pesticides (Malahlela *et al.,* 2021; Idris *et al*., 2022). This is important in combating varieties of agricultural and stored grain insect orders, most notably the Coleoptera (beetles), Diptera (mosquitoes and flies), Hymenoptera (ants, bees, and wasps), and Lepidoptera (butterflies and moths) pests (Dassanayake *et al*., 2021).

Based on delivery system

Nano-sized intelligent delivery systems have been developed and implemented in agricultural systems with the aim of regulating the release of active ingredients against certain pests (Anakwue, 2019). Nano-delivery techniques can be used alone or in combination, depending on the needs of the pest management programme. These depend on the following;

i. target-specific release,
ii. time-controlled release, or
iii. self- or remotely-regulated systems.

The broad categories of nanosuspensions (Cui *et al.*, 2016), nanoemulsions (*Du et al*., 2016), and nanocapsules (Cao *et al*., 2016) include a variety of intended and produced ways of nanoformulated pesticides.

Formulations of Nanobiopesticides used as Control of Stored Grain Insect Pests

A range of formulations, including nanoemulsions, polymer-based nanopesticide formulations, and products incorporating engineered nanoparticles (such as metals and metal oxides), have been proposed for the management of pests associated with stored grain insects (Mondal, 2020; Singh *et al*., 2021).

Nanoemulsions

Insect pests of stored grain such as *Sitophilus oryzea*, *Tribolium. castaneum*, rust-red flour beetle among others have been used in the management of pests using nanoemulsions (Hashem *et al*., 2018; Mohammed &Nasr, 2020). These target-specific nanoemulsion formulations have the potential to increase the efficacy of botanical insecticides intended for commercial use (Frederiksen *et al.,* 2003; Anjali *et al*., 2012). Adding adjuvant and surfactants to these formulations can improve their efficacy. They require less active components and inert material because of their high water solubility, which facilitates the solubilization of hydrophilic and lipophilic molecules. As a result, they are substantially less expensive. Furthermore, throughout a wide temperature range (-1055°C), storage stability is fairly high (Pavoni *et al*., 2019).Tests have been conducted on essential oil nanoemulsions as a synthetic pesticide substitute. Nanoemulsions have addressed issues including volatility, degradation, and poor water solubility linked with the use of synthetic pesticides (Martín *et al*., 2010). It is expected that these kinds of formulations will yield greater results than bulk materials (Anjali *et al*., 2010, 2012). Essential oil-based nanoemulsions have demonstrated their great effectiveness in managing storage pests during the last ten years (Pavoni *et al*., 2019). For example, a eucalyptus oil nanoemulsion containing the aqueous filtrate of *Karanja* and *Jatropha* at concentrations of 300 and 1,500 ppm killed 88%–100% of adult *Tribolium. castaneum* in less than 24 hours (Pant *et al*., 2014); a *Pimpinella anisum* L. (Apiaceae) essential oil–based nanoemulsion containing 81.2% of (E)-anethole demonstrated the toxicity of (LC50 _ 9.3% v/v) and dramatically decreased the number of rust-red flour beetle offspring (*Hashem et al*., 2018; Mohammed and Nasr, 2020). In addition, a study carried out by Adak *et al* (2020), an essential oil nanoemulsion of eucalyptus oil with a particle size of 8.57 nm was found to have greater insecticidal efficacy against *T. castaneum*. Accordingly, eucalyptus oil nanoemulsions tested at lethal concentrations (LC50) of 0.56 and 0.45 $\mu L/cm^2$, (cm2 or cm3) shown extreme toxicity against *T. Castaneum* (Adak *et al.,* 2020). They also underwent centrifugation, thermodynamic stability, heating, cooling, freezing, and thawing experiments. The effectiveness of *Achillea biebersteinii*,*A. santolina*, and *A. mellifolium* essential oil nanoemulsions against *T. castaneum* larvae and adults was demonstrated by Nenaah (2014). Moreover, *Achillea biebersteinii* essential oil nanoemulsion shows some extra effectiveness against red flour beetle adults. Additionally, jojobe (*Simmondasia chinensis*) nanoemulsion (Sh *et al*., 2015); purslane oil nanoemulsion (Sabbour *et al*., 2016); and oregano and thyme essential oil–based nanoemulsion (Hossain *et al*., 2019) are some additional essential oil nanoformulations that have demonstrated efficacy against stored insect pests. According to reports, *Sitophilus oryzae*, flat grain beetles, and confused flour beetles are acutely harmful to the sweet orange (*Citrus sinensis*) and sweet flag oil (*Acorus calamus*) nanoemulsion (spontaneous emulsification) (Giunti *et al*., 2019; Dhivya *et al*., 2019). The essential oils nanoformulations of *Mentha spicata* L. and *Mentha pulegium* L. demonstrated a death rate between 86.03% and 95.47 %, respectively, when tested against *T. castaneum* (Heydarzade *et al*., 2019). According to Choupanian *et al*. (2017), neem oil (*Azadirachta indica* A. Juss) nanoemulsion demonstrated 85–100% efficacy against *S. oryzae* and 74–100% efficacy against *T. castaneum.* The exposure of *T. confusum, T. castaneum* larvae, and *T. molitor* adults to 1,000 ppm of *Hazomalania voyronii* essential oil-based nanoemulsion (HvNE) for seven days, resulted in the corresponding mortality rates of 92.1, 97.4, and 100.0% (Kavallieratos *et al*., 2021a). The efficacy of NE (3% (w/w) made up of isofuranodiene essential oil (EO) of *Smyrnium olusatrum*demonstrated strong adulticidal effects against *T. molitor* as well as larvicidal activity against *T. castaneum* and *T. confusum*, with concentrations of 98.6, 97.4, and 93.5% at 1,000 ppm after seven days of exposure, respectively(Kavallieratos *et al*.2021b)

The extract of *Mentha longifolia* with a concentration of 14–36ppm nanoformulation in the form of an emulsion killed *Ephestia kuehniella* larvae (Louni *et al.*, 2018). Comparably, the same *M. longifolia* formulation was more lethal as a fumigant against *Callosobruchus maculatus*, effectively eliminating 50% of the egg population in 4.7 days at a concentration of 9μL/L (Louni *et al*., 2019). Nanoformulations of the Tasmanian blue gum (TBG) EO effectively controlled the population of *C. maculatus* (Ya-Ali *et al*., 2020). Nanoemulsions prepared by extracting essential oils of Anise (*Pimpinella anisum*), Artemisia (*Artemisia vulgaris*), fennel (*Foenicum vulgare*), garlic (*Allium sativum*), lavender (*Lavandulaangustifolia)*, mint (*Mentha piperita*), rosemary (*Rosmarinus officinalis*), and sage (*Salvia officinalis*) showed considerable toxicity against *T. confusum*. Recent research has shown that persistent application of essential oil nanoformulations against storage pests may result in habituation that is decrease in response to stimulus after being repeatedly exposed to nanoformulations (Giunti *et al*., 2021). The application of nanoemulsions of essential oils from sweet orange (*Citrus sinensis*), mint (*Mentha x piperita*), and fennel (*Foeniculum vulgare*) against *Rhyzopeta. dominica*, revealed that habituation happened (Giunti *et al.,* 2021).Furthermore, cold aerosol and gel nanoemulsion from the oil of*Allium sativum*, also demonstrated the highest toxicity. *Pimpinella anisum* nanoemulsion was shown to be the most effective repellent against *T. confusum*, but the application of garlic oil nanoemulsion showed the highest level of toxicity against insect pest of stored grain (Palermo *et al.,* 2021). When nanoemulsion made with *Achillea biebersteinii* essential oil at 10 μL/L was applied to second larvae of *T. castaneum*, there was total mortality (100%) after four (4) days of exposure (Almadiy, 2021).

Polymer-Based Nanobiopesticide Formulations

The development of polymer-based controlled release formulations of fungicides, herbicides, and insecticides for pest management programmes, with emphasis on the protection of the photo-liable active components is a going debate (Neri-Badang & Chakraborty, 2019). Polymer-based delivery systems function as a protective reservoir covering that promotes a controlled release of active ingredients and increase the spreading of active ingredients in aqueous media (Kalia *et al.,* 2020). The discharge of the active substances is affected by the nanocarrier's degradation, the bonding between the active chemicals and the carrier, and meteorological conditions leading to controlled optimization and efficiency of the process (Kumar *et al.,* 2019). The advantage of utilizing polymers is the ability to protect and stabilize active compounds against unstable substances like essential oils and secondary metabolites found in plants; degradation occurs as a result of contact with air, water, light, or extreme temperatures thus rendering them less effective. Recently, a variety of polymer nanoformulations have been created, including chitosan-based nanoformulations, nanofibers, nanocapsules, nanospheres, nanogels, and micelles. Since polymeric nanoparticles are biodegradable and environmentally benign, they are most frequently utilized to encapsulate active substances (Kumar *et al*., 2017; Ramasamy *et al*., 2017). In the current context, the most crucial attribute that a polymer needs to possess is biodegradability. Because polymer-based nanoformulations employ fewer organic solvents and surfactants in their formulations, they can make best use of the effectiveness of their active components while reducing their harmful impacts on the environment (Li *et al.,* 2018). Schematic representation of the major mechanism of action adopted bypolymer-based nanobiopesticide formulations to protect crop from storage pests is shown in fig (2). With this, researchers are especially drawn to polymer-based nanoformulations because of their intricate delivery systems, which combine several active components with various modes of action, biocompatibility, and biodegradability (Tong *et al*., 2017). The primary polymers used in nanobiopesticide formulations include polyesters (poly-ε-caprolactone and polyethylene glycol) and polysaccharides (chitosan, alginates, and starch) (Kashyap *et al*., 2015; Rani *et al*., 2017; Kumar *et al*., 2018). In recent times, goatweed, citronella oil, and moringa oil extracted from *Ageratum conyzoide*after transformation into nano-oils via polymerization technology were tested at a concentration of (0.5%) on third-instar *Ryzopertha. dominica* larvae and demonstrated the highest accumulative mortality (99.0%, 89, and 87%, respectively) (Sabbour *et al*., 2020b). Numerous studies have demonstrated that essential oils, which were previously ineffective in preventing storage insect attacks, became highly effective products when combined with nanotechnology. Similarly, Jesser *et al.* (2020) observed the temperature following application while investigating the connection between the insecticidal properties of essential oils (EO) or essential oil-loaded polymeric nanoparticles (EOPN).

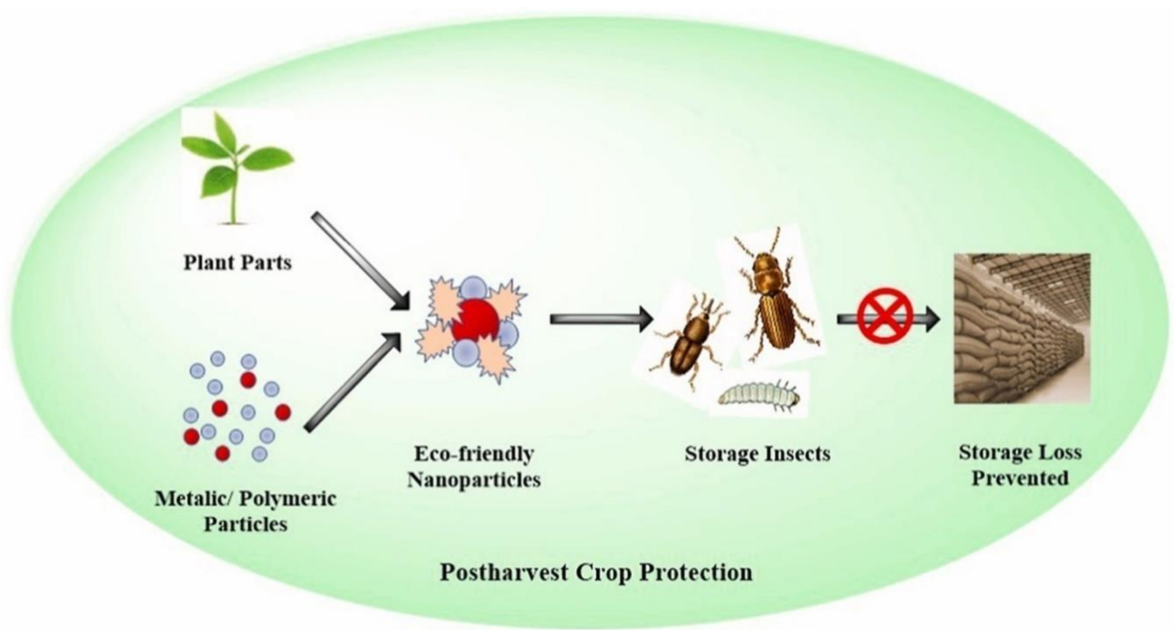

Figure 2: Schematic representation of the major mechanism of action adopted bypolymer-based nanobiopesticide formulations to guard the crop from storage insect pests.
Source: Bighneswar and Chandan (2023)

Chitosan-Based Formulations

Chitin is one of the major prevalent natural polysaccharides usually converted to chitosan (CS) through deacetylation process (Badawy *et al*., 2021). Chitosan-based formulations have been effective against storage insect pests. A nanogel based on myristic acid (MA) and chitosan (CS) that was loaded with *Carum copticum* (L.) essential oil (EO) was found to be effective against *S. granarius* and *T. confusum*, and the studies revealed that the toxicity effect increased with increasing exposure time (Ziaee *et al*., 2014). Chitosan nanoparticles encapsulated in peppermint oil (PO) were discovered to be extremely poisonous to *S. Oryzae* (Rajkumar *et al*., 2020). The encapsulation of *Melissa officinalis* essential oil in a chitosan matrix enhanced its fumigant action (LC50 = 0.048 µL/mL) and potently inhibited *T. castaneum* growth (EC50 = 0.043 µL/mL) (Upadhyay *et al*., 2019). Similarly, *R. officinalis* and *Zataria multiflora* essential oil nanoparticles encapsulated in chitosan and polycaprolacton shown good control of confused flour beetle (Ahsaei *et al*., 2020).

Nanocapsules

Nanocapsules are nanoscale vesicular systems typically ranging from 10 to 1000 nanometers in size. They consist of a core encapsulated by a polymeric or lipidic shell for delivering pesticides or nutrients in a controlled manner. Nanocapsules can protect the encapsulated substance from degradation, enhance their stability and improve bioavailability (Chaudhary, 2014). Whennanoencapsule formulation made using *Cuminum cyminum* polymerized oil/water emulsion (using poly urea formaldehyde) are sprayed continuously on rust-red flour beetles for seven days, it produced an LC50 value of 16.25 ppm, which is lower than the value of oil tested alone (Negahban *et al*., 2012). Furthermore, a formulation loaded with *Rosmarinus officinalis* essential oil was found to be effective against *T. castaneum* (Khoobdel *et al*., 2017).At doses of 7.0 and 3.5 mg/g, *Sitotroga cerealella* were completely destroyed by the cysteine protease nanocpasule of Albizia procera (ApCP) (Batool *et al*., 2021). Similarly, it was discovered that *Z. multiflora* and *Eucalyptus globulus* essential oils, when nanoencapsulated, were successful in suppressing *Ephestia kuehniella* (Emamjomeh *et al*., 2021). At 166 ppm, nanoparticles encapsulated with essential oil of *Artemisia haussknechtii* exhibited 100% mortality (Khanahmadi *et al.*, 2017). *Lavandula angustifolia* can also be used since it is comparable to cumin oil, and the combination of nanocapsulated form of *Cuminum cyminum* essential oil and reduced amounts of phosphine controlled 50% population of *Sitophilus granarius*and *T. castaneum* at a concentration of 42.51 and 78.99 µL/L, respectively (Bayramzadeh *et al.*, 2019).

Metal-based Nanoformulations

These metal formulations are typically made from metal ions or clusters that serve as nucleation centres and are joined by organic ligands (Chen *et al*., 2017). A number of outstanding characteristics of metal-based encapsulation, or metal-organic frameworks (MOFs), include high surface/volume ratios, numerous pores, pore size adjustability, effective surface chemistry, high thermo-stability, and multiple topologies (Chen *et al*., 2017; Nehra *et al*., 2019; Vellingiri *et al*., 2017). The development of metal-based NBPs is motivated by notable features of nanotechnology, such as the presence of multiple active sites for the release of bioactive molecules, ion exchanging properties, high adsorption ability, and exceptional electronic characteristics (Masoomi *et al*., 2016; Xia *et al*., 2015).

Mechanism of Action of Nanobiopesticides (NBPs)

NBPs toxicity potential against a variety of insect pests are well documented however, specific details regarding their method of action against insects are scarce in the literature (Rai *et al*., 2014; Athanassiou *et al*., 2018). Since NBPs are relatively new and have not been thoroughly explored, very few studies have been conducted to examine the toxicokinetics or toxicodynamics of these compounds against pests that cause damage to storage grain. Toxicodynamics describes the physiological, biochemical, and molecular effects of the compounds and the mechanisms in which they are involved, whereas toxicokinetics primarily describes the movement and changes an insecticide goes through inside an organism such as absorption, distribution, metabolism, and excretion (Alzogaray and Zerba, 2017). A little number of studies has examined the mechanism of action of silver, metal, gold, alumina, silica, and graphene oxide nanoparticle-based nanopesticides against insects (Benelli, 2018). Silver nanopesticides are known to reduce protein synthesis and gonadotropin release, which results in developmental damages and reproductive failure by either up- or down-regulating key insect genes (Nair & Choi, 2011). By attaching to S and P in proteins and nucleic acids, respectively, metal nanoparticles decrease membrane permeability by causing organelle and enzyme denaturation, which is followed by cellular death. In addition to their ability to block trypsin, gold nanoparticles have effects on growth and reproduction (Patil *et al*., 2016; Small *et al.*, 2016). Insect dehydration results from the binding of silicon dioxide and aluminium oxide nanopesticides to the insect cuticle, which is accompanied by the physico-sorption of lipids and waxes (Debnath *et al.*, 2011; Arumugam *et al.*, 2016). In order to induce the *Tribolium confusum* insect to get dehydrated and die, the nanozeolite formulation attached itself to the insect's body and proceeded to crack and scratch its cuticle (Ibrahim & Salem, 2019). Stadler *et al*. (2017) investigated the toxicity of nanostructured alumina as well as its method of action against *S. oryzae*. Triboelectric forces were found to have connected charged nanostructured alumina to the beetle cuticle, causing the insect to become dehydrated as a result of the wax coating being absorbed by surface area phenomena as schematic demonstrated in Figure 3.

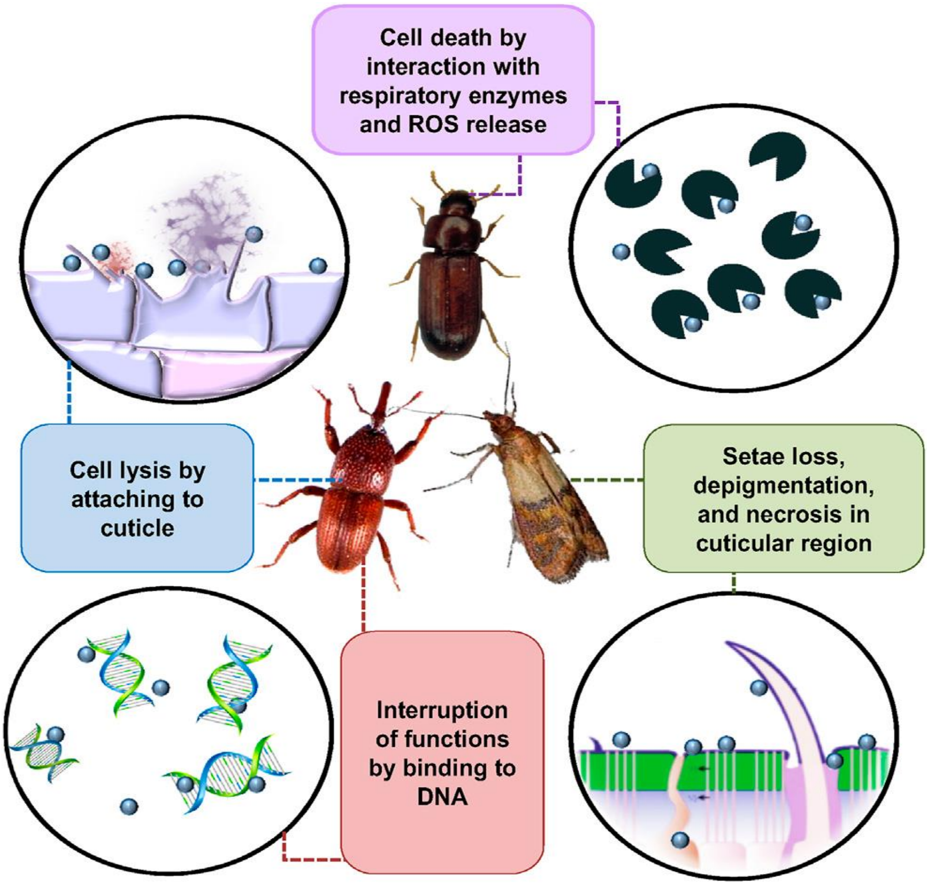

Figure 3: Mechanism of action of nanoparticles against some storage insect pests
Source: Jasrotia *et al.,* (2022)

Advantages of Nanobiopesticides in Post Harvest Management

The synergy between botanicals and NBPs is the most effective ways to control insect pests in an environmentally friendly approach (Chhipa, 2019). The use of agrochemicals at the nanoscale in agriculture, through the use of nanopesticides, nanofertilizers, nanosensors, and nanoformulations, has altered conventional agricultural practices (Aouada & De Moura, 2015; Panpatte *et al*., 2016; Scott *et al.,* 2018; Pirzadah *et al*., 2019; Singh R. P *et al.*, 2021). The properties of NBPs vary significantly from those of conventional pesticides due to their tiny size and larger surface area. These properties can be used to develop an effective structure with several advantages, including the potential for better interaction and mode of action at a target site of the desired pest. Products with a nanoscale size show higher selectivity against the target pathogen without compromising the compound's bioactivity. Pest penetration may also increase as a result of their enhanced toxicity (Priya *et al.,* 2018). As long as the formulation can deliver the target insecticide at the ideal concentration for extended periods of time, using nanoparticle application minimises drifting and leaching problems and permits the use of a lower concentration of active component per area. It can deliver a prolonged supply of active ingredients that may stay effective for longer periods of time with a smaller amount of active ingredient applied per region (Singh *et al.,* 2020).Moreover, the application cost is decreased as a result of the lower dose need (Shekhar *et al*., 2021). In contrast to traditional pesticide formulations, nanoformulations are specifically made to release the biocide in a regulated and focused way and to make insoluble or poorly soluble active ingredients more soluble (Margulis-Goshen & Magdassi, 2013; Ragaei and Sabry, 2014; Garg & Payasi, 2020).

Recent reports suggest that the nanoparticles used in the formulation of NBPs are particularly beneficial to agriculture (Omole *et a*l., 2018). Several agrochemicals have been stabilized by using them as active components and transporters; the resultant products include nanopesticides, NBPs and nanofertilizers (Chaudhary & Sharma, 2019; Chaudhary *et al*., 2021a). Grillo *et al*. (2021) and Konappa *et al.* (2021) have reported the use of pesticides derived from nanomaterials, such as magnesium oxide, magnesium hydroxide, copper oxide, and zinc oxide, in the aqueous extracts of *Chamaemelum nobile* flowers, *Punica granatum* peels, green peach aphid (GPA), and *Olea europaea* leaves, for the purpose of controlling insects. Additionally, *Helicoverpa armigera*, the causal agent of cotton bollworm, has been studied in relation to silver nanoparticles produced from *Euphorbia hirta leaf extract* (Devi *et al.,* 2014). It has also been documented that copper oxide and zinc oxide nanoparticles can inhibit *Alternaria citri*, which is the agent responsible for the plant's citrus black rot disease (Lasso-Robledo *et al.,* 2022). Furthermore, on a potato dextrose medium, Sardar *et al*. (2022) employed individual and combined zinc oxide and copper oxide to prevent citrus black rot disease. Copper nanoparticles have been shown to have fungal and insecticidal effects on *Tribolium castaneum*, a pest that damages grains (El-Saadony *et al.,* 2020). Furthermore, due to microbial attack, freshly picked, highly damp, unpreserved yields may deteriorate rapidly, but a novel and cutting-edge approach to reduce post-harvest losses is the application of nanobiopesticides. Hence, edible coatings are applied on food as liquids, usually by dipping the item into a material that serves as a solution and is created by the structural medium (carbohydrate, lipid, protein, or mixture). By impeding dehydration, disrupting breathing, enhancing textural characteristics, supporting the preservation of volatile fragrance molecules, and reducing microbial development, NBPs prevent untreated foods from getting bad. When applied to various meals, edible nanocoatings offer a barrier against the flow of gases and moisture while also supplying flavours, colours, enzymes, antioxidants, and agents that prevent browning, all of which have the potential to extend the shelf life of harvested agricultural produce (Zambrano-Zaragoza *et al*., 2018). Many methods, including magnetic resonance imaging, fluorescence spectroscopy, and microscopy using characteristics such as the composition of NBPs, surface charge, concentration, size, physical and chemical alterations are been used to study the main interactions that take place between plants and nanoparticles (Chhipa, 2019).

Limitations and Challenges in the use of Nanobiopesticides (NBPs)

The fact that NBPs reduce environmental contamination by lowering pesticide application rates and losses is one factor supporting their use over traditional pesticides (Jasrotia *et al.,* 2018; Luiz de Oliveira *et al.,* 2018). Despite their potential, there are still a lot of unanswered questions about NBPs. These include potential long- and short-term consequences on biodiversity, non-target organisms, soil and ground water quality, human and animal health, and non-target organisms (Ashraf *et al.,* 2021). However, the extended persistence and increased toxicity of these NBPs can provide a new issue. Small droplet sizes can potentially cause the nano-droplets to evaporate before they reach their target. Another important topic that needs research is how nanobiopesticides interact with various animals, plants, and microbes at different trophic levels. Three main obstacles to the commercialization of NBPs are market acceptability, legal compliance, and use in real-world settings.

The release of the active ingredients into the environment is determined by the characteristics of the nanocarriers and the way the active ingredient disperses inside the nanoformulation matrix. According to reports, non-target organisms may be impacted by delayed release of nanoparticles over an extended period of time (Kah *et al.,* 2013). There hasn't been much discussion about the use of non-biodegradable nanocarriers like metal and metal oxides, as most nanocarriers utilized in nanobiopesticides are either naturally occurring polymers, polysaccharides, or lipids that break down quickly (Kah & Hofmann, 2014).In order to create pesticidal nanoformulations for standard NBPs formulations, hazardous organic solvents must be used, and these solvents are extremely hazardous to the environment.

There are no rules governing the registration or release of nano-products onto the market. Since it is important to comprehend the behaviour, efficacy, toxicity, physicochemical qualities, and environmental consequences of NBPs, standard guidelines for their evaluation prior to registration and commercialization must be developed immediately. Because NBPs formulations are widely used, the scientific community is becoming increasingly concerned about their toxicity and potential effects on the ecosystem. Further study and research in these areas is therefore necessary. As a result, supplementary work needs to be done to investigate and determine the best path for creating safe and more intelligent nanoformulations.

Future Prospects of Nanobiopesticides in Post Harvest Management

The use of biopesticides as a feasible alternative to traditional chemical pesticides is becoming more and more popular in crop protection due to its negative effects. Nanotechnology in agriculture promises to revolutionize farming methods without negatively impacting the environment. As a botanical derivative, NBPs offer additional benefits such as enhanced pesticide efficacy, easier biological system penetration, target specificity, and controlled release. Studies have demonstrated that the application of nanoparticles is useful in preventing quick grain degradation during storage as well as in safeguarding crops in the field. Despite their many benefits, nanoparticles can have negative effects if not utilized carefully. These include low selective toxicity, low inorganic nanoparticle biodegradability, and the development of pesticide resistance in non-target animals. Certain nanosystems are still in the early stages of research and development, slight information is known about the environmental fate of these nanoparticles and the potential harm they could cause to organisms that are not their proposed targets. The potential effects and ripple effects that nanomaterials may have on non-target creatures, the environment, and the creation of environmentally safer nanopesticides require more consideration. Researchers should do more in-depth studies on safety measures, food mutations caused by nano-structured materials (NSMs), the toxicity of nanoparticles in human cells, and the effects of nanoparticles on the environment (Chhipa *et al*., 2017b; Sahoo *et al.,* 2021).

It is necessary to evaluate the idea of "green nanotechnology," which is promoted as one of the advantages of nanoproducts, by looking into any possible hazards associated with their use. In addition to evaluating these goods' safety and dangers, it is important to consider their sustainability. This includes taking into account the manufacturing costs, environmental effects, and renewability of all materials used in synthesis and manufacture (Watson *et al*., 2011; Chowdappa & Gowda, 2013). Additionally, it is equally important to look into other constraints like a slower rate of production, the possibility of entering another natural ecosystem—agriculture—the effect of a non-homogenous composition on stability, a lack of understanding of the dynamics involved in these problems, and, last but not least, the negative effects resulting from the size, solubility, and putative binding of the nanoparticle's toxicity. Future studies in nanotechnology that result in the creation of NBPs ought to concentrate on the creation of clever formulations to overcome the drawbacks of traditional formulations, the creation of environmentally friendly, green NBPs chemistry, the development of technologies for the affordable and commercial production of NBPs. The practical utility of nanoformulations is evaluated by comparing them with conventional analogues in the field, evaluating the ecotoxicological effects of NBPs, and finally establishing a legal and regulatory framework that will allow the safe introduction of NBPs into agriculture.

CONCLUSION

Food security remains difficult despite enormous efforts due to scarce resources and population growth. Understanding botanical pesticides will stop the widespread use of chemo-synthetic pesticides and the adoption of NBPs. Compared to conventional agrochemicals, smart NBPs may offer benefits like reduced dosage requirements, increased solubility, and targeted active ingredient delivery that increase eco-protection while reducing negative environmental consequences (Dubey & Mailapalli, 2016). The assessment and investigation of botanical pesticides, which will satisfy the needs of safe and effective agrochemicals, will contribute to a promising future of nano-formulations of naturally occurring, biologically derived, and effective active molecules. Generally speaking, the most promising avenues for the creation of novel and enhanced products are made possible by nanotechnology. However, several scientific groups challenge the public's worry about health dangers related with nanotechnology products, which calls for more research. It is expected that nanotechnology will play an important part in attaining sustainable agriculture and will increase its potential in offering workable substitute agricultural solutions. However, in order to successfully manage agricultural produce after harvest and give humans access to wholesome, highly nutritious food, further investigation and comprehension on NBPs are required.

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