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MINI-REVIEW

Nanotechnology in pest management: advantages, applications, and challenges

Hesham A. Yousef[1] · Heba M. Fahmy[2] · F. Naser Arafa[3] · Mahmoud Y. Abd Allah[4] · Youssef M. Tawfik[4] · Kholoud K. El Halwany[4] · Basant A. El-Ashmanty[2] · Fatma Sh. Al-anany[5] · Maha A. Mohamed[2] · Mirna E. Bassily[4]

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Abstract

Pests are one of the most concerning biotic problems in agriculture and food. Humans are constantly in search of new strategies to control them. Traditional strategies like integrated pest management used in agriculture are insufficient, and applying chemical pesticides has adverse effects on animals and human beings in addition to declining soil fertility, pest resistance, elimination of natural enemies, environmental pollution, loss of biodiversity, and human health hazards. Using nanotechnology in pest management as an alternative strategy can be one of the most promising ways to overcome the problems of using conventional chemical pesticides. Although they still face many obstacles and uncertainties and More research is needed to improve their development, evaluation, and regulation, The advantage of nanotechnology as an alternative for the management of insect pests is increasing efficiency against target organisms and low toxicity of nanocides to non-target organisms, highlighting the insufficient collateral environmental damage were reported in this work. It also provides selective, targeted, and long-term-controlled release of formulated nanomaterial, which is ecologically more viable. So, using nanotechnology for insect pest management is considered environmentally sustainable and an excellent insect control strategy in green agriculture.

Keywords Nanopesticides · Nanoparticles · Advantage · Insect pest control · Nano-agriculture · Environmental and toxicological risks

Introduction

Nanotechnology is a new promising field extensively used. It opens many opportunities in various applied sciences, such as medicine, biology, pharmaceuticals, engineering, agriculture, and genetic engineering, making life easier in this era (El Wakeil et al., 2017; Bayda et al., 2019; Khan et al. 2023).

One of the significant difficulties faced by the sector of agriculture worldwide is the production of lasting food for a rapidly increasing human population and will need to rise by 70% by 2050 to feed the billions of people living on the planet (FAO; IFAD; UNICEF; WFP; WHO 2019; Farmery et al. 2021). Consequently, the increased utilization of fertilizers and pesticides has become crucial to optimizing agricultural productivity. Because of a lack of adequate environmental technologies for pest control, insects, weed pests, and plant pathogens destroy more than 40% of all potential food production, despite applying nearly 3 million tons of pesticide annually and a wide range of biological control agents (Srishailam et al. 2022).

However, pesticides have a fatal effect on the targeted insects or pests (Christopher et al., 2020); about 98% of insecticides and 95% of herbicides are sprinkled on crops that reach their targeted and non-targeted species, water, soil, and air (Delon 2019). Recently, pesticide contamination

✉ Hesham A. Yousef
heshamyousef.eg@cu.edu.eg

[1] Entomology Department, Faculty of Science, Cairo University, Giza, Egypt

[2] Biophysics Department, Faculty of Science, Cairo University, Giza, Egypt

[3] Zoology and Chemistry Department, Faculty of Science, Al Azhar University, Cairo, Egypt

[4] Biotechnology Department, Faculty of Science, Cairo University, Giza, Egypt

[5] Botany and Microbiology Department, Faculty of Science, Cairo University, Giza, Egypt

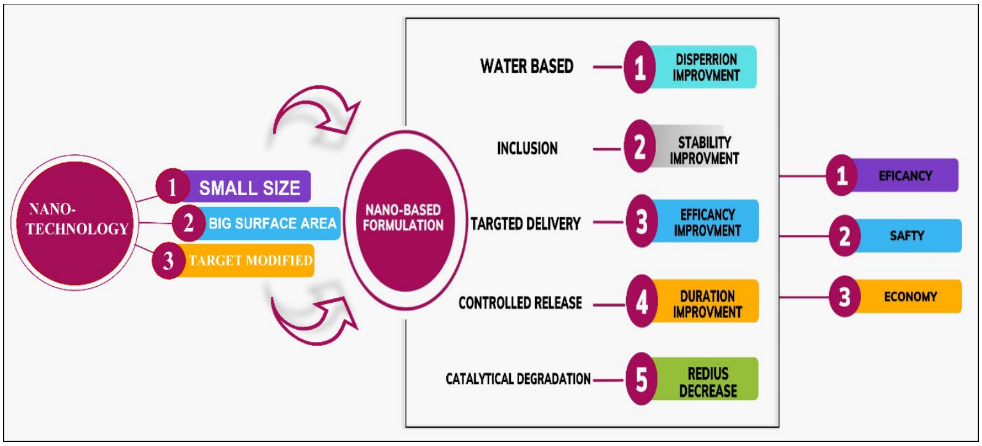

Fig. 1 Beneficial enhancements of nano-pesticide formulations (based on Urkude 2019)

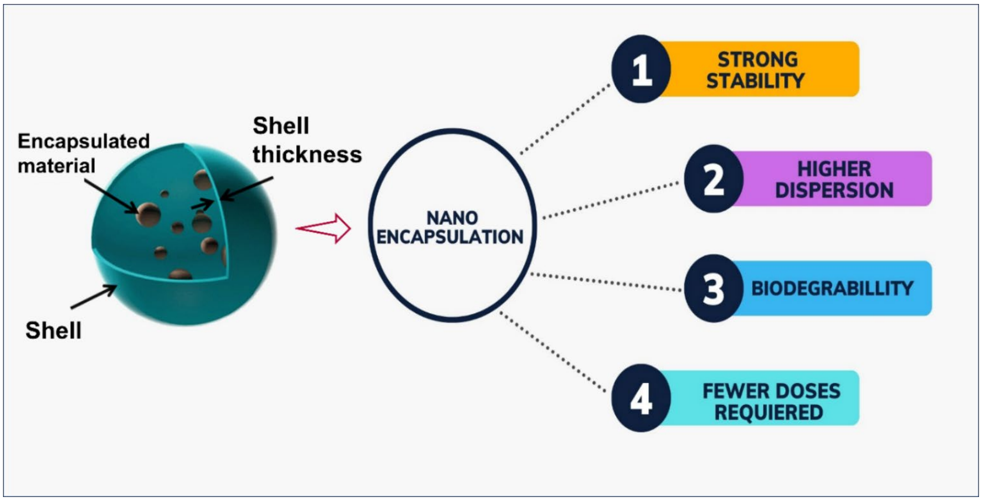

Fig. 2 Nanoencapsulation and benefits (based on Urkude 2019)

has become a notable concern due to what diseases it causes (Richardson et al., 2019). Nanotechnology can diminish the amount of these active complexes' utilization to preserve the environment and human health and reduce the cost of yield production. (Srishailam et al. 2022; Wang et al. 2022)

This review aimed to cover the conventional strategies utilized to manage pests and insects and the potential of nanoparticles in controlling pests and insects as recent approaches to nanotechnology with refereeing to environmental and toxicological risks.

Nanopesticide advantages and disadvantages

Conventional pesticides have coarse carrier particles, poor stability, poor dispersion, and poor biological activity, and their usage rate for the targeted crops is less than 30% (Udoh and Umoh 2016; Ocho et al. 2016; Tong et al. 2018; Sun et al. 2019; Zhou et al. 2023). In addition, more than 90% of pesticides run away into the environment and inhabit agricultural products in the application process (Urkude 2019). Nano-pesticides commenced marching into agriculture and food production (He et al. 2019). Analysis by Wang et al. (2022) showed that nanocides may be more efficient, sustainable, and flexible with fewer adverse environmental effects than traditional analogs. He has demonstrated advantages over conventional insecticides, such as increasing efficiency against target organisms by 31.5% and 18.9% in field trials. The low toxicity of nanocides to non-target organisms is less than 43.1%, highlighting the insufficient collateral environmental damage (Wang et al. 2022). The control delivery system facilitates the sustainable release of the effective ingredients at the targeted distinction for a prolonged period, raising targeted delivery pesticide effectiveness and efficiency into action targets, such as insects, crops, and pathogens (Hayles et al. 2017). The beneficial enhancements of nano-pesticide formulations are represented in Fig. 1 (Urkude 2019).

The nano-carriers of pesticides not only enhance the stability and dispersion of pesticides but also facilitate the active ingredients of pesticides to the targeted organisms to enhance their bioavailability (Ali et al., 2014; Udoh and Umoh 2016; Ocho et al. 2016; Sharma et al. 2017; Mohasedat et al. 2018; Tong et al. 2018; Xu et al. 2022). These advantages and benefits could compensate for the shortcoming and deficiencies of large dosages and poor efficacy of conventional pesticides in practical applications (Fig. 2).

Environmental issues of conventional pesticides impact biodiversity

Significant efforts are to eliminate insects that harm the crops with minimal side effects on non-target organisms such as soil, water, and humans (Fig. 3.) (Sun et al. 2019).

The target organisms of pesticides

As a systemic insecticide, Imidacloprid is highly effective and can block the microtinergic neuronal pathway (Sumon et al. 2018; Yang et al. 2021). A lot of studies proved that nano-Imidacloprid is more effective than conventional insecticide against *Aphids Myzus persicae nicotianae* (Assemi et al., 2014); *Sitophilus granarius* (Sabbour 2018), *Rhyzopertha Dominica* (Sabbour 2018); *Rhopalosiphum Padi* (Abd Elwahab et al. 2020). Nano-Imidacloprid showed less toxicity than nano-chlorpyrifos towards honeybee workers (El-Masarawy et al. 2020) and observed the changes in the characteristics of honeybee *Apis mellifera* L., N-Imidacloprid had the lowest damage on the wings horizontally and mouthparts while nano-Chlorpyrifos recorded a negative effect on the abdomen length. El-Helaly et al. (2020) found that chlorpyrifos and their nano compounds are more toxic than Imidacloprid, and using Citronella can save honeybees for a long duration. Also, nano-chlorpyrifos showed more toxicity than Nano-imidacloprid in the digestive system of *Rhynchophorus ferrugineus* (RPW), which is considered one of the most dangerous insects of palm species (Dhouibi et al., 2017; Abd El-Fattah et al. 2019). It leaked to the epithelial cells causing damage to their nuclei. Larvae had more damage than adults (Abd El-Fattah et al. 2019).

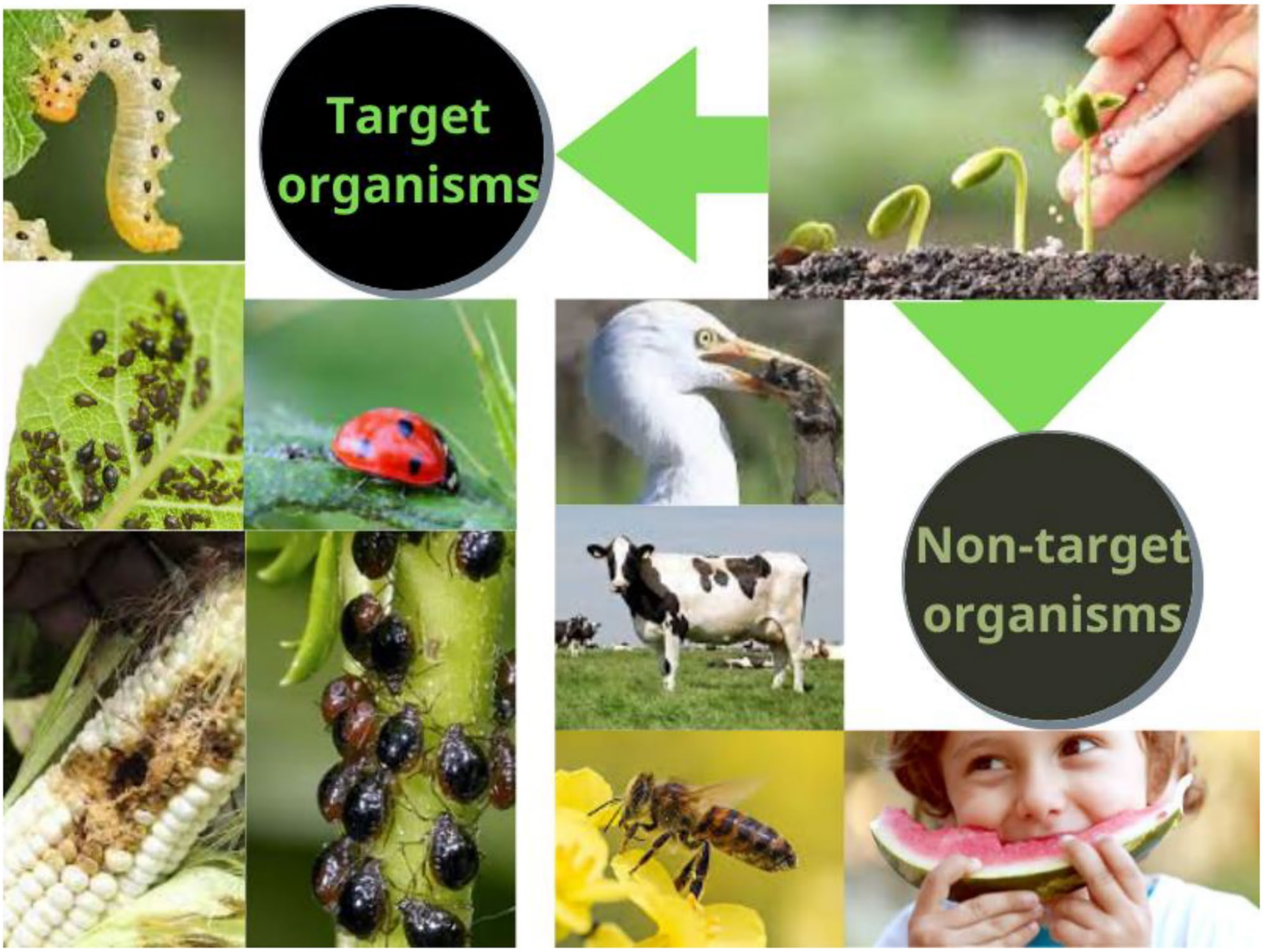

Fig. 3 The impact of pesticides on the organisms in the environment

Table 1 Examples of nanoparticles as delivery systems for pesticides

Nanoparticle	Pesticide used	Pest	Stimuli	Advantage	Reference
Mesoporous Silicon-Based Nano-Carriers (MPSNPs)					
Trimethylammonium-functionalized MSN	2,4-Dsodiumsalt	*Cucumis sativus* L.	pH Ionic strength Temp.	The stability.The ability to stand up to physical stress, such as the surrounding variations of temperature and pH in their environment.	Cao et al. 2017
MSNs-chitosan@ prochloraz nanoparticles.	Prochloraz	*P. digitatum*, *P. italicum* *G. candidum*	pHEsterase	The toxicity of the nanoparticles to zebrafish was reduced more than 6-fold compared with that of prochloraz technical.	Liang et al. 2018
Nano-organized biogenic silica particles	Thymol	*Escherichia coli* (gram -ve) and *Staphylococcus aureus* (gram + ve).	pH Ionic strength Temperature	The ability to promote the solubility and absorption of pesticides by plants	Mattos et al. 2018
Solid Lipid Nanoparticles (SLN)	Lambda-cyhalothrin (LC)	F. candida	PHIntrinsic properties of LN	Narrow size distribution. Good physical stability for at least 4 months. No risk to the growth of crops and the reproduction of invertebrates.No significant effects are expected on soil biota. Excellent compatibility of LC and lipid matrix of LN.	(Zhao et al. 2022)
Nano-Capsules	thifluzamide and validamycin Dual-Functionalized Pesticide Nano capsule	*Rhizoctonia solani*		Better spreading performance on foliage Enhanced bioactivityHigh stability	Cui et al. 2020
Nanogels	LC@NFBs	foliar applications		Simple low cost biocompatible	Cao et al. 2021
	The pheromone ME (Methyl eugenol) nanogel	*B. dorsalis*		no harmful and toxic chemicals are usedno direct human contact	Bhagat et al., 2013
Micelles					
Triblock copolymer shell	Essential oil components (EOCs)	Permethrin-resistant Pediculus human capitis (head lice).		Twelve months all the formulations remain stable. These formulations were effective against head lice, with mortality ranging from 30–60%.	Lucia et al. 2017
2-nitrobenzyl carboxymethyl-chitosan succinate micelles	Diuron	-----------		High rate of photo-controlled release (96.8%) for up to 8 h (at pH 7) under solar radiation stimulus.	Ye et al. 2015
CMCS-DEACMS micelles	2,4-dichloro phenoxy acetic acid (2,4-D)	*Cucumis sativus* L.	Sunlight	displayed similar root growth inhibition compared to free 2,4-D, and the root length and fresh weight were reduced to around 23% and 50% compared to the control plant with stable water over 200 days without any precipitation.	Feng et al. 2020
(PBMS-PEG))	Avermectin		Temp.		Han et al. 2019
Liposomes	CYM-loaded sterosomes	*Saccharomyces cerevisiae*		Overcome the barriers to drug stability and drug efficacy.	Zhang et al. 2021b
Nano-Emulsions	Vitex Negundo essential oil	*Avena fatua* and Echinochloa crus-galli weeds	+	physical stability, high bioavailability-irritant in nature	Mustafa and Hussein 2020a
	norcanthridin nanoemulsions	*Plutella xylostella*			Zeng et al. 2019
	Aniba essential oils	*Aspergillus flavus*, *Aspergillus niger* and *Fusarium solani*			Zeng et al. 2019
	Alpha-cypermethrin deltamethrin, lambda cyhalothrin, and permethrin	*Culex pipiens* larvae		high toxicity (1.5–2-fold) decrease in the field application rate by half-value	Taktak et al. 2021

The different types of nanomaterials used to combat the insect pests were illustrated in Fig. 4.

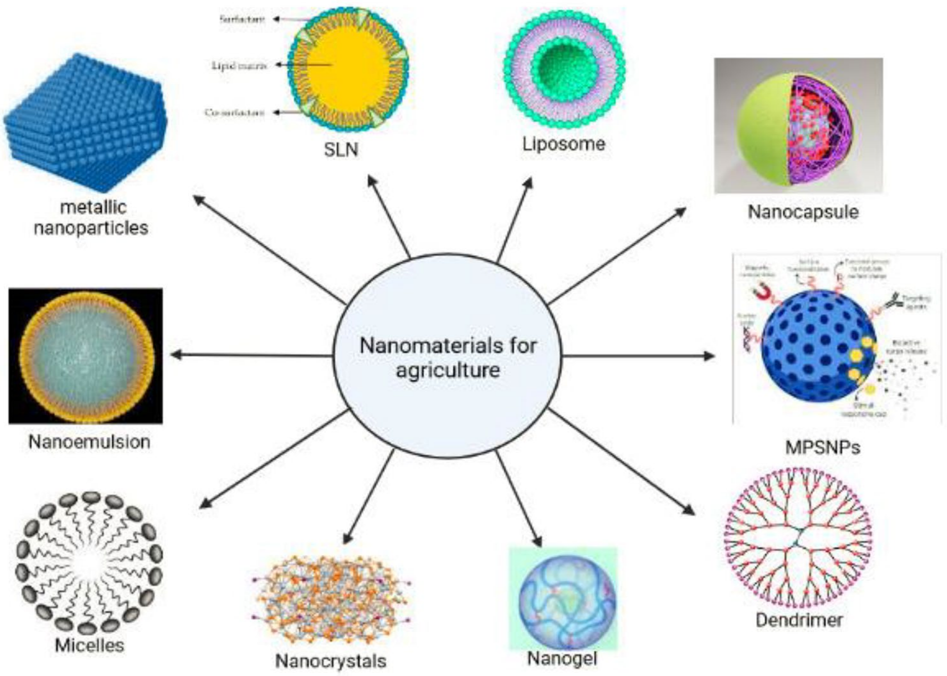

Fig. 4 Types of nanomaterials used to combat pests in agriculture

The non-targeted organisms of the pesticides

Pesticides have harmful effects on the environment and non-targeted species. Their beneficial effects have been exceeded by risks linked to pesticide use. Pesticides have dragged on non-target species and affect biodiversity, ecosystems of animals and plants, water and land-based food, and humans (Poudel et al. 2020). Natural enemies have a significant role in controlling the level of.

pest populations. The destruction of these enemies can worsen problems with pests (Dara 2019; Nazir et al.,2019). Natural enemies who typically control pests are also affected in certain instances, resulting in secondary pest outbreaks, for example, parasitoids and predators (Gill and Garg 2014; Sánchez-Bayo 2021).

Impact of pesticides on the biodiversity of soil

Invertebrates represent more than 22% of soil-living animal species (Alves et al., 2017). Earthworms, for example, have a significant role in improving and preserving the structure of the soil by forming soil channels for soil aeration and drainage (Gill and Garg 2014), affecting microbial biomass and indirectly soil activity (Medina-Sauza et al. 2019), and they are susceptible to insecticides. (Miglani et al., 2019). The pesticides also trigger indirect crop loss and the direct loss of insect pollinators due to the absence of sufficient pollinator populations (Aoun., 2020).

Impact of pesticides on biodiversity of water

Pesticides are toxic for fish and non-target organisms in aquatic ecosystems. They are toxic by themselves, but they also interact with stressors, including the harmful flowering of algae. The overuse of pesticides indicates a decrease in populations of various fish species (Kumar et al., 2021).

Impact of pesticides on human health

Pesticides can enter the body via inhalation of pesticide-containing aerosols, dust, vapor, food/water, ingestion, and direct contact with the skin through oral exposure. However, long-term and indiscriminate usage led to a severe impact on wellness. The unspecific nature and ineffective application of pesticides make humans, particularly infants and children, highly susceptible to pesticide adverse effects (Mahmoud et al. 2016).

Environmental issues of nano pesticides impact on biodiversity

Nanomaterials have the potential to be a fundamental component of most industrial products, fertilizers, medicine, and medication research due to their unique features. Until now, there is now enough information about nanoparticle toxicity and its impact on human health. Nanomaterials can pass through biological membranes, access organs, and enter the bloodstream via inhalation or ingestion. This could result in biochemical and genotoxicity (Forest 2022). Nano-pesticides can improve the efficiency of pesticides with controlled release to the targeted pathogen. Still, it has been reported that only 0.1% of the nano-pesticide is delivered to the targeted pathogen. In contrast, the rest, 99.9%, goes to the environment surrounding the pathogen, leading to a loss in biodiversity, water, and soil pollution and increased resistance to pathogens and pests (de Albuquerque et al. 2020). The main reason for the toxicity of nanoparticles of nano pesticides is their small size; for example, silver nanoparticles can cause cytotoxicity in human lungs, leading to lung cancer due to silver release into the medium; silver nanoparticles can also cause a wide range of toxicities, including genotoxicity, developmental toxicity based on particle size, cytotoxicity, and inflammation (Parveen et al. 2021).

Also, the nanoparticle's shape has a role in its toxic effect simulation-based computation showed that form and shape Charging on NPS would speed up their translocation process v the membranes of cells up to 60 times (Zhang et al. 2021a). Nano-particles of ZnO in the shape of the nanorods are more toxic to the human lung epithelial cells than in their spherical form; likewise, gold nano-particles have the same function, but they are different in their shape, which led to the difference in toxicity between them as the spherical gold nanoparticles are more toxic than the rod-shaped ones and this may be due to the quick release of the functional molecule in the spherical shape (Egbuna et al. 2021).

Examples of nano pesticides effects on non-targeted organisms

Copper-based nano pesticides (CuO, Cu, Cu $(OH)_2$) have great attention nowadays. Carley et al. (2020) found that their effect on the target, the Terrestrial agroecosystem, was limited, and the non-target wetland (aquatic community) was affected a lot, especially among protists. Zhao et al. (2020) reported that at 500 mg kg^{-1} soil of CuONPs, denitrification is inhibited, NO3- accumulation increases, and the emission rate of NO_2 decreases.

A mixture of Chlorpyrifos and zinc oxide (bulk and nanoparticles) is designed and measured on artificial and natural soil over two generations of earthworms. The toxicity differs by the soil type, size of used nanoparticles, and the generation of earthworms. The next generation of earthworms can adapt to a single toxicant more than a mixture of toxicants (García-Gómez et al. 2019). They found that the mix of Chlorpyrifos and zinc-oxide nanoparticles had more harmful effects than using them separated on the growth and reproduction of *Eisenia Andrei.* From another view, Nano-formulation has got attention to synthesis and study of the effect of these compounds on the soil. Nano-formulation of the atrazine was less toxic than atrazine on *Enchytraeus Crypticus* (Oligochaeta) soil (Gomes et al. 2019).

Impact of nano-pesticides on the human

Nano-pesticides that go to the surrounding environment of the targeted pathogen form a significant risk to human health. Nanoparticles in these pesticides can enter the human body through the respiratory tract or nose and then go to the lungs. The nasopharyngeal area can catch nanoparticles with a size range from 10 to 20 nm(Gulati et al. 2022). The smaller the particle, the more toxicity it will have if the same composition and crystalline structure. Small nanoparticles can cause inflammation and cell proliferation followed by fibrosis and consequently form tumors (Ettlinger et al. 2022). Many nano-particle types improve the expression of viral receptors, leading to the hyper-activity of macrophages, which results in severe inflammation. Still, at the same time, some nanoparticles, such as TiO_2 and SiO_2 reduce the expression of bacterial and viral receptors, decreasing the human body's resistance to bacteria and viruses (Mahon et al. 2020).

Entomological nanotechnology applications

Nanotechnology offers new agrochemicals and distribution technologies and promises to minimize chemical doses to increase crop production. The available agrochemicals effectively improve crop productivity and suppress pests and diseases. But it requires a high dose of indiscriminate application and affectivity (Khan et al., 2017). The nanotechnology application aims to reduce the dose of agrochemicals through encapsulation, coating, etc. (Ayyaril et al. 2023).

Nanotechnology for insect pest control

Recent studies indicate that engineered nanomaterials (ENM) platforms can provide successful strategies for controlling and managing insect pests and weed species. Nanogenic formulations containing ENM in traditional insecticides/herbicides can improve target species' active ingredient penetrability, solubility, stability, and controlled release properties by nano-emulsification and nanoencapsulation (Adisa et al. 2019). Increasing the precision and accuracy of the distribution of active components, like nano fertilizers and antimicrobials, can minimize a load of material released into the system, reducing unwelcome effects on non-target organisms and the environment (Yin et al. 2018). The atomic structure controls nanoparticles and affects their size, shape, and orientation for reactions to the targeted tissues (Baig et al., 2021). Nanoparticles have novel features such as extraordinary strength, high chemical reactivity, and high conductivity (Baig et al., 2021). Nanopesticides are found in different forms (e.g., micelles and particles) and may consist of organic (e.g., polymers) and/or inorganic ingredients (e.g., oxides of metals) (Harish et al. 2022).

Types of nanoparticles used as biopesticides in controlled-release formulations

Based on Ragaei and Sabry (2014); Harish et al. (2022), these nanoparticles are classified into:

Nanospheres: the most common type of nanomaterials used in biocidal release formulations, aggregate, in which the active material in the polymer matrix is homogeneously distributed.

Nanocapsules: aggregate which concentrates the active compound lined with a matrix polymer near the core.

Nano gel: hydrophilic polymers that absorb significant amounts of water (usually cross-linking).

Micelles: an aggregate created by hydrophilic and hydrophobic molecules in aqueous solutions.

Beneficial enhancements of nano pesticides to control insect pests

Nano-agriculture focuses on farming that applies nano-sized particles with unique properties to boost crop production (Batsmanova et al., 2013; Scott and Chen 2013). Nano-encapsulation is another part of nanotechnology that offers a variety of desirable features, including reduced human exposure to active ingredients, controlled release, longer residual concentrations, elimination of organic solvents, and increased efficacy (Hack et al. 2012). Due to the development of Nanoscience in insect pest control, encapsulation formulations have modernized the pesticide application as it decreases the doses compared to the traditional pesticide to achieve full impact with more target-oriented pesticide action. The core material (pesticide) is coated in this process, encapsulated by capsulation material or shell, and the pesticide size reduces to the nano size.

The benefits of nanotechnology are enormous in all stages of production, storage, packaging, processing, and transport of agricultural products. In particular, the recent development of the nanotechnology-based synthesis of slow or managed-release pesticides is efficient over other pesticide delivery vehicles (Harish, et al. 2022). One of the critical aspects of precision farming is the application of agrochemicals to plants using control delivery systems.

The objective of regulated delivery techniques is to release the calculated quantity of required and adequate quantities of agrochemicals over time and achieve maximum biological competence to reduce losses and harmful effects (Shojaei et al. 2019). Nanoparticles release agrochemicals to plants using control delivery systems, compared to traditional pesticide formulations, where more than 90% of pesticides enter the atmosphere and remain in agricultural products during the application process. The control of the delivery system enables the continuous release of the active ingredient at the target site for a prolonged period, thus improving the efficiency of pesticide delivery to action targets such as plants, pathogens, and insects (John et al. 2017), increasing the solubility and the dispersion for fat-soluble chemicals in aqueous solution (Anjali et al., 2012), reducing the use of pesticides and the frequency of treatment by extending the lasting validity duration (Yu et al. 2017), enhancing bio-efficacy, reducing chemical inputs to plants, solving the problem of non-target toxicity and improving chemical stability by limiting photo-degradation for light-sensitive compounds (Anjali et al., 2012). Continuous pesticide release protects ecosystem biodiversity (John et al. 2017). Plant growth promotion, seed germination, and crop improvement in the traditional practices are being reported to be successfully replaced by carbon nanotubes application as the regulators of plant growth and seed germination (Zheng et al. 2005; Khodakovskaya et al. 2013).

Evolutionary trends in nano pesticides

The rapid advances in nano-pesticide science have prompted several international organizations to consider possible concerns related to the use of nanotechnology for crop safety. Creating experimental protocols to produce reliable fate properties will be needed to investigate the bioavailability and durability of nano pesticides (Wang et al. 2022). Evaluation and refinement of the current environmental risk assessment approach should be considered in recent research to minimize the toxic effects of chemical pesticides and the production of intelligent nano-systems to reduce agricultural problems such as environmental imbalance, food security, and productivity. These nano-systems with a high level of controlled release pattern usability over a long period can help with eutrophication and residual pesticide accumulation (Shekhar et al. 2021).

In addition, nano pesticides have increased the solubility and stability of the active ingredient, allowing for more efficient pest control (Ojha et al. 2018). However, there is still room for improvement in the like:

a. (a) The development of smart nano pesticides will offer many solutions to the agrochemical industry, such as active ingredient solubility, stability, controlled release, and targeted distribution, as well as a better understanding of nano pesticide's fate in the field.

b. (b) To optimize the effectiveness of nano pesticides, they should be developed using green chemistry and environmental protection principles.
c. (c) To improve processes for upscaling nano pesticides to commercial levels.
d. (d) Nanopesticide environmental impact assessment to determine toxicity level. Regulations for using nanomaterials in agriculture are being improved (Ojha et al. 2018).

Toxic mechanism of nanomaterials

The harmful mechanisms of nanomaterials in living things are unclear. According to studies, the following four elements are primarily responsible for these materials' harmful effects. **First**, nanomaterial particles can quickly enter cells and pass through the cell membrane. As a result, they can interfere with a cell's regular physiological processes and inhibit photosynthesis (Abdel-Aziz et al. 2019; Abd El-Azeim et al.,2020). **Second**, some nanomaterials—such as nanosilver, nano-copper, and nano zinc ions—can release harmful ions on their own [(Bratovcic, A., 2019) & (Rajput et al., 2020)].

Oxidative damage is the third element. Reactive oxygen species (ROS), quickly produced by nanomaterials, are incredibly reactive. ROS can damage the mitochondria's antioxidant defense mechanism, cause oxidative stress, functional protein inactivation, and even cell death, which can interfere with normal physiological processes(Zulfiqar et al. 2019; Abdel-Aziz et al. 2019; Bratovcic, A., 2019; Abd El-Azeim et al.,2020; Baranowska-Wójcik et al., 2020; Rajput et al., 2020; Staron et al., 2020; Grillo et al., 2021).

The biological amplification effect is the fourth element. Nanomaterials may accumulate in organisms at high trophic levels in the food chain, a process known as biomagnification (de Oliveira et al. 2015).

Internalization of NPs (endocytosis and exocytosis)

Various parameters, including NP composition, size, shape, stiffness, and surface chemistry, influence the internalization of NPs. These characteristics are crucial for NP stability in the biological milieu, and they can also affect cell–NP interactions and subsequent absorption (Sousa De Almeida et al. 2021). Cell membranes choose the endocytosis pathway due to the nanoparticle's shape, size, and surface chemistry. The size of the nanoparticle is essential to determine targeting, circulation time, saturation concentration, and the uptake mechanism. Also, the type of nanoparticle can affect the uptake mechanism (del Prado-Audelo et al. 2022). Understanding cell–NP interactions, endocytosis, and intracellular trafficking has vastly improved in recent years.

Smaller NPs are primarily taken in by clathrin and caveolae-mediated endocytosis, whereas larger NPs and agglomerates are taken in via macropinocytosis and phagocytosis(Sousa De Almeida et al. 2021). Smaller nanoparticles can enter and leave the cell more easily. Nanoparticles with spherical shapes are internalized more than nanoparticles that are cylindrical. Nanoparticles with a positive charge have a higher rate of endocytosis than neutral, negatively charged nanoparticles (Sousa De Almeida et al. 2021).

Nano-copper pesticides

Copper-based nanoparticles have been used in many fields, such as industrial engineering, environment, medicine, and agriculture. The production of new nano-pesticides aims to synthesize nano-pesticides with a high effect and low environmental pollution. The cytotoxicity of nano-copper pesticides is not completely clear (Vignardi et al. 2020a, b).

Cytotoxicity of CuNPs

Usually, copper is one of the nutrients required for the body, but if the intake of copper exceeds the normal range of the body, it will induce toxic effects like jaundice and hemolysis and may lead to death. Also, it will cause harmful effects on the gastrointestinal tract and respiratory tract. (Ingle et al. 2014). CuNPs can be used as nano pesticides, nano-herbicides, and nanomedical products based on CuNP (Rai et al. 2018; El-Saadony et al. 2020). The critical role of all Cu-based pesticides is to release toxic Cu ions. Conventional Cu pesticides, CuCl2 or CuSO4 included, are highly effective for agricultural pest management (de Oliveira-Filho et al. 2004; Vignardi et al. 2020a, b). To minimize environmental impacts, nano pesticides based on Cu are designed to be as efficient and ecologically less toxic than traditional products as they release affecting Cu ions very slowly, thus repelling pests while exposing non-target species to relatively low Cu concentrations (Keller et al. 2017; Vignardi et al. 2020a, b). Copper-based pesticides usually include 56% organic Cu, 34% CuSO4, 6% Cu2O, and 4% CuO by weight.

Nano-silver pesticides

The usage of silver nanoparticles (AgNPs) in different fields of life has highly increased in the last few years, and this is due to the unique chemical and physical properties of silver. AgNPs have many biological applications, such as antifungal, antibacterial, antiviral,…. etc. (Yin et al. 2020)

Cytotoxicity of AgNPs

One of the essential properties of AgNPs is their toxicity and their effect on human and animal health; many studies published in the last decade show that AgNPs have a highly toxic effect on many cell lines and some aquatic organisms. For example, some algal species possess a higher sensitivity toward the AgNPs than that towards Ag+. Still, when cysteine is added to form a complex with silver ions, it decreases the toxic effect of AgNPs and Ag^+. They suggested that silver ions released from the AgNPs become less harmful when forming a complex with sulfur and organic complex (Stensberg et al. 2011).

Cytotoxicity of polymeric nanoparticles (PNPs)

Polymeric Nanoparticles are sub-micron particles with a size range from 1 to 1000 nm. In agriculture, polymeric nanoparticles are used to deliver chemicals to crops to control pests and improve crop yield. Polymeric nanoparticles improve the targeting ability, which reduces the pollution and toxicity of the surrounding environment, protects the active material against the surrounding environment, is highly soluble in physiological conditions, has a controlled release of the active substance, and improves the dynamic material's efficiency. Examples of the polymers used in the delivery system are poly (epsilon-caprolactone), poly (lactide-co-glycolides), and polyethylene glycol. (Acharya and Pal 2020).

Mechanism of action of PNPs

Controlled release systems are new developments that have piqued the attention of commercial and science communities worldwide in recent years. Alginate and chitosan are classic pH-responsive nanocarrier devices (Román et al. 2016). The interaction between these two biopolymers is exploited in the ionic gelation process to create nanocarriers made of alginate and chitosan. When a system is made up entirely of a single biopolymer, changes in pH can cause repulsion between the polymer chains due to similar charges, resulting in the greater or lesser opening of the polymer mesh (swelling) and thus affecting the active agent's release(Ofridam et al. 2021). These mechanisms describe how most the pH-responsive release systems work (Reyes-Ortega 2014).

Conclusion

Nanotechnology has the potential to transform existing technologies in various fields, including pest control, as it has shown an outstanding ability to manage the release pattern of pesticide-active ingredients, making them more effective for long-term functionality and overcoming agricultural runoff and residual pesticide accumulation issues. As a result, it is possible to conclude that nanotechnology can give green and eco-friendly alternatives for pest management that do not harm the environment. Consequently, nanotechnology is considered one of the promising and emerging fields that can potentially alter the current situation of the agriculture and food sector with the aid of recently developed approaches.

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Data Availability All data needed to support the conclusions are included in this article. Additional data related to this paper can be requested from the corresponding author (heshamyousef.eg@cu.edu.eg).

Declarations

Conflict of interest The authors declare no competing interests.

Informed consent Consent to participate and consent to publish were obtained from all individual participants included in the study.

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