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Nano-pesticides: Emerging Opportunities for Sustainable Agriculture and Food Security

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Abstract

The excessive application of conventional pesticides has detrimental effects on soil health and the environment. Chemical remnants of these pesticides damage the soil environment by impacting nontargeted organisms and, with time, decreasing soil fertility. Thus, to effectively manage insect pests in agricultural fields without deterioration of the surrounding biota, nanotechnology has proven to be a significant substitute for conventional chemical pesticides. Compared with conventional pesticides, nanopesticides reduce and control excess agricultural inputs and maintain environmental balance in addition to improving the shelf life and nutritional content of produce. This technology offers more potential for sustainably enhancing worldwide food production. Currently employed conventional pest management strategies are inadequate and have several harmful impacts on the environment and humankind. There is a serious need for the development of safe and promising formulations and the implementation of a regulatory framework for the safe use of nanopesticides. This chapter addresses the need for nanopesticides for sustainable agriculture, their environmental efficacy, their associated benefits and disadvantages, and the prospects of nanopesticides.

Keywords: Pesticides, Nanopesticides, Sustainable agriculture, Food security, Environmental protection

Introduction

Sustainable agriculture and food security are two of the most important concerns confronting global society today. Agriculture is one of the significant components of the national economy in underdeveloped nations ^[1, 2]. Food production rates become a larger and larger part of a country's GDP (Gross Domestic Product). The quantity of fertilizers and pesticides used has an impact on the rate of food production in addition to other elements such as climatic variability, soil quality, environmental temperature, and water availability ^[3, 4, 5, 6]. To improve agricultural productivity sustainably for the growing global population, it is crucial to control the application of conventional chemical fertilizers and pesticides in addition to addressing changing environmental circumstances ^[7]. Globally, according to the Food and Agriculture Organization of the United States (FAO), between 20-40% of crop yield is lost annually due to pest and plant diseases. This loss amounts to totals of \$220 billion and \$70 billion, respectively ^[8]. The term "pesticides include a wide range of compounds including insecticides (chlorinated hydrocarbons, organophosphates, carbamates-insecticides, pyrethroids, botanical and biological products, etc.), fungicides and bactericides (inorganic, dithiocarbamates, benzimidazoles, triazoles, diazoles, diazines, etc.), herbicides (phenoxy hormone products, triazines, amides, carbamates- herbicides, dinitroanilines, urea derivatives, sulfonyl urea, bipiridils, uracil, etc.), rodenticides (anti-coagulants, cyanide generators, hypercalcemics, narcotics, others not otherwise classified), molluscicides, nematocides, various plant growth regulators", etc ^[9, 10]. Before the 1960s, organochlorine insecticides were primarily used to control various diseases. However, these compounds were soon replaced by synthetic insecticides such as organophosphates in the 1960s, carbamates in the 1970s and pyrethroids in the 1980s, which contributed greatly to pest control and enhanced agricultural output⁹. Before long, the successful use of these synthetic chemical pesticides created a havoc with nontarget species (human) and other life forms ^[11].

Reliance on chemical pesticides

Our agricultural systems for effective crop disease management and adequate food production have long relied on pesticide-based interventions^[12]. From the perspective of total volume used, the global requirement, production and utilization of pesticides has continuously increased over several decades, as has the quantity of pesticides applied per hectare^[13,14,15] (Fig. 1). Nonetheless, pesticide consumption per unit crop output has remained unchanged^[14]. While contemporary pesticides exhibit greater biological activity per gram of active ingredient used, pesticide application efficiency on a worldwide scale has not improved. Reports show that the utilization of pesticides in 2010 was almost 50% greater than that in 1990, with the worldwide requirement for pesticides reaching 4.2 million tons in 2019, with herbicides being the most commonly used pesticides^[3,16]. Throughout the world, America (42.7%), Asia (33.3%) and Europe (17.9%) have been the major consumers of

pesticides since 1990-2022^[16] (Fig. 2). Traditional pesticides have been shown to have insufficient water solubility, are non-targeting and rapidly release active component^[17]. Among the total pesticides applied in agricultural fields, only 0.1% reach their target pest, while 99% overflows into the surrounding ecosystem^[18]. The toxicity caused by pesticides impacts environmental balance and health of animals and human. Pesticides have been linked to cause 70% human poisoning and more than 50% freshwater ecotoxicity^[19]. Breakthroughs in scientifically sound and evidence-based technologies create new prospects for addressing the issues of sustainable agriculture. Thus, advanced advancements in scientifically sound and evidence-driven technologies are needed to promote the development of sustainable agriculture with improvements in the food supply and to decrease collateral environmental damage^[20].

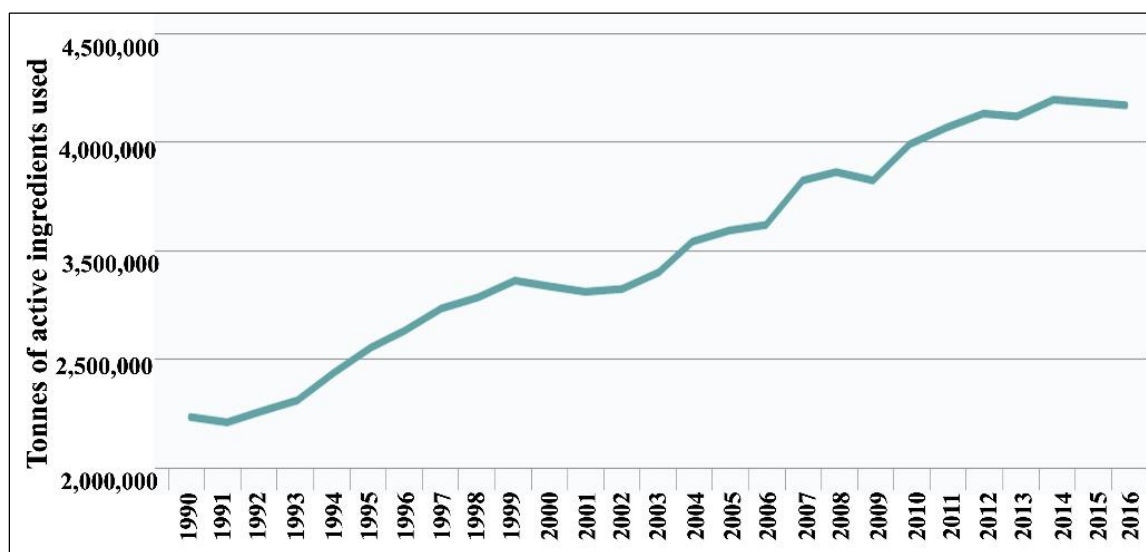


Fig 1: The global use of pesticides in agriculture has increased from approximately 2.3 MT of active ingredients in the early 1990s to more than 4 MT in 2016^[21]. MT: million tons.

The world's rapidly growing population and increasing demand for food have made it imperative to find innovative ways to increase agricultural productivity while minimizing environmental effects. Nanotechnology, which involves the manipulation of matter at the nanoscale, is a potential approach to address these problems^[22]. Numerous potential uses for nanotechnology exist in industry, agriculture, medicine, and materials science, among other fields^[23]. The fields of nanotechnology research that are now expanding the fastest include plant science and agriculture^[24, 25, 26, 27, 28]. One of the key applications of nanotechnology in agriculture is the development of nanopesticides for

improving agricultural production^[29]. These compounds are formulated with nanoparticles and offer several advantages over traditional pesticides^[30]. However, nanoparticles are used as efficient delivery systems for exogenous insecticidal components to increase plant health, broaden the insecticidal spectrum, decrease pesticide application, extend the duration of action, and reduce pollution in the environment. NPs are also employed as adjuvants to help distribute chemical or botanical pesticides (double-stranded RNAs and toxic *Bacillus thuringiensis*), increasing their effectiveness and lowering the quantity of pesticides used^[31, 32, 33, 34, 35].

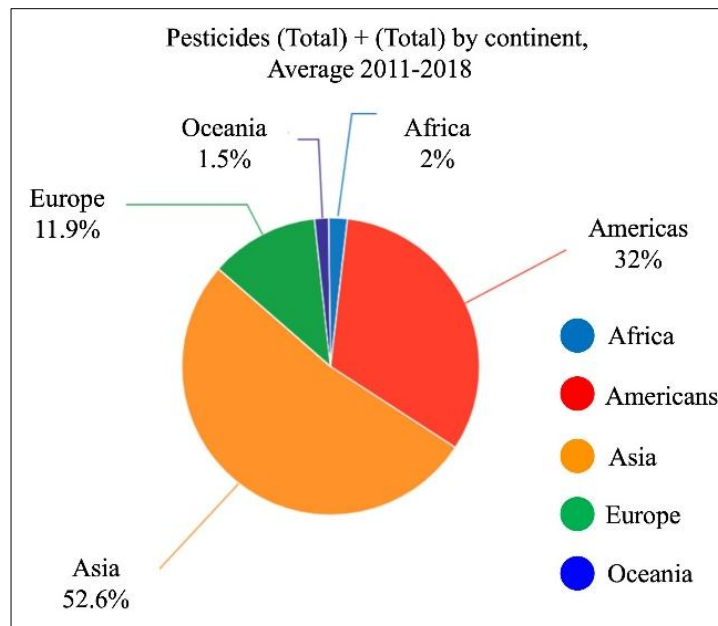


Fig 2: Total agricultural use of pesticides on different continents ^[36].

Pesticides are utilized in India's agriculture and public health sector ^[37]. In Asia, India is the second-largest pesticide manufacturer. Compared with the rest of the world, India consumes 3.75%, i.e., 62,193 tonnes of the total 3.39 million tonnes of pesticides per year ^[38, 39]. Pesticides used in India differ significantly from those used internationally. Globally, herbicides constitute approximately 50%, followed by fungicides (22.5%), bactericides (20.4%) and plant growth regulators (1.2%). On the other hand, since 1999–2000, insecticides have been used the most in India (51.4%), followed by fungicides and bactericides (32.6% and 15.8%, respectively). The low use of herbicides has contributed to the availability of cheap labor and limited adaptability to genetically modified crops ^[40, 41]. Currently, roughly 64% of agricultural land worldwide is at risk of pesticide contamination from more than one active ingredient. Out of these 31% are at high risk ^[42].

Pesticides are used in around 5 billion kg per year worldwide, with significant implications on biodiversity, nontarget creatures, and the food chain. In the human body, acute and chronic health problems arise from exposure to pesticides via consumption, breathing, skin contact and cutaneous absorption ^[43, 44]. According to WHO estimates, due to negligent handling and application of pesticides, roughly 3 million cases of severe poisoning with 220,000 deaths occur each year ^[45, 46, 47]. Among these 70% of the deaths are the result of professional hazards, which occurs to workers in agricultural fields, the pesticide industry and eradicators of house pests ^[48] (Fig. 3). The consumption of food and water contaminated with pesticide residues causes nonoccupational exposure, whereas environmental exposure occurs through water, soil and air contaminated from leaching, runoff and spray drift ^[49].

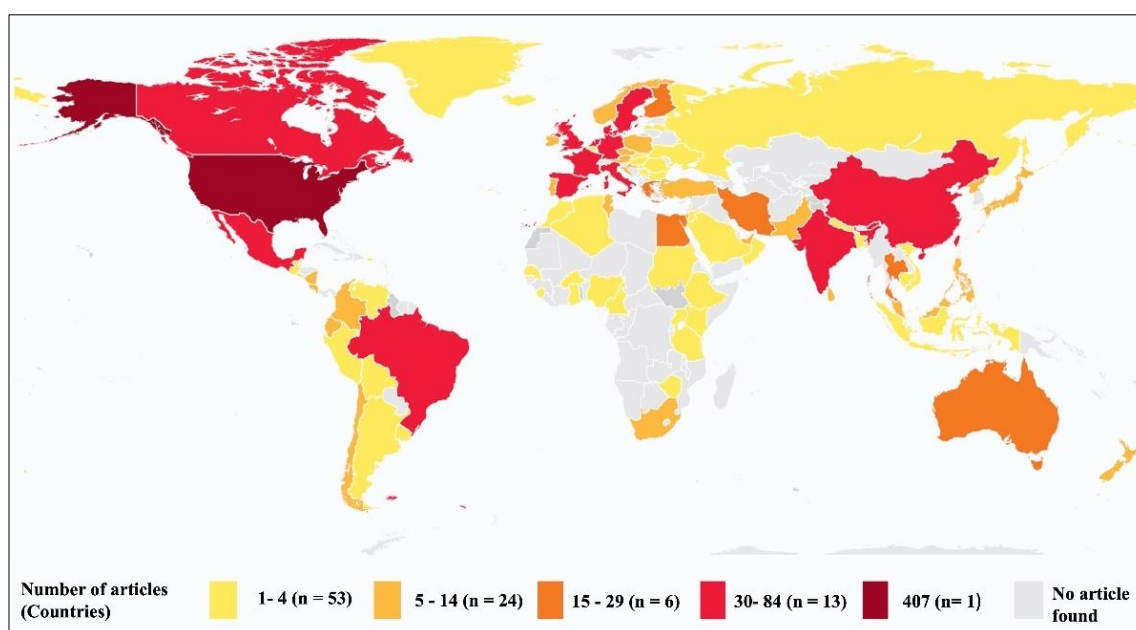


Fig 3: Number of articles published on occupational pesticide exposure and various health consequences between 1993 and 2017, each nation acting as the study location ^[50].

Issues with conventional pesticides

Pesticides are important components of agriculture worldwide. Its use during the Green Revolution resulted in a significant increase in crop yield in addition to the use of high-yielding crop varieties ^[12]. Currently, research is being conducted worldwide on the dangers of pesticide usage and its toxicity on living organisms and the ecological balance ^[51]. Research indicates that only 0.1% of pesticides (used through different methods) reach the effective target, while 99.9% disperse into the neighboring environment. This leaching leads to soil and ground water contamination and disturbs the ecological balance ^[52, 53]. Indiscriminate use of pesticides eliminates helpful insect pollinators (such as bees, butterflies and moths), natural predators and birds, resulting in an increase in harmful pest populations.

The solubility of pesticides also poses another challenge in agriculture, as this is mandatory for good diffusion of the active ingredient in the liquid phase, which is essential for crop-dusting ^[54]. The liquid phase, especially water, is a very inexpensive, readily accessible and environmentally friendly medium for applying pesticides. However, numerous pesticides have either low solubility or complete insolubility in water ^[55]. As a result, more pesticides and often various organic solvents are needed to ensure uniform dissolution and even application. Furthermore, this impediment escalates cultivation costs, increases ecological contamination and increases human exposure ^[56]. The effectiveness of the spray also depends on the stability of the active component, as several biotic and abiotic factors can break down pesticides even before they reach their target sites. The accumulation and toxicity of pesticides are also influenced by the chemical stability of the active ingredients. Those compounds that have high stability are more resistant to breakdown and hence are more likely to accumulate in aquatic organisms ^[57]. Many of these pesticides are lipophilic, such as dichloro-diphenyl-trichloroethane, methoxychlor, dicofol, heptachlor, chlordane, endosulfan, aldrin, dieldrin, and endrin, which allows them to accumulate in fat tissues and infiltrate the food chain easily ^[58]. At each successive level of the food chain, the amount of pesticide bioaccumulation increases. Humans are more susceptible to neurological impairment, hormonal disorders, and other severe and prolonged health effects ^[59]. Sometimes entire crop failure can also occur because of the phytotoxic effects created by the use of multiple pesticides at the same time ^[60]. To navigate the difficulties associated with conventional pesticides, researchers have shifted to nanolevel pesticides, which offer several advantages in terms of efficacy, durability, targeted delivery, stability and environmental risk-reducing features.

Nanopesticides: A boon for current times

Galanakis ^[61] describes sustainable agriculture as “the efficient production of safe, high quality agricultural products, in a way that protects and improves the natural environment, the social and economic conditions of farmers, their employees and local communities and safeguards the health and welfare of all farmed species”. Sustainable agriculture, when integrated with social responsibility, economic viability and environmentally sound approaches can offer a holistic plan for achieving food security and meeting current demands ^[62]. Sustainable agriculture relies primarily on pest management, which preserves not only the environment but also human and animal health ^[63]. The

adoption of sustainable practices can help reduce the environmental impact, increase biodiversity, improve human health and ensure long-term agricultural productivity ^[64].

Nanopesticides are a rapidly developing field in agriculture. It offers promising solutions to the challenges associated with conventional pesticides and thus has the potential to revolutionize traditional pest management practices ^[65]. These nanoparticles have numerous advantages over conventional pesticides, including improved efficiency, lower environmental impact, resistance management, economic benefits and sustainability support. These properties make them more appealing choices for sustainable and effective agricultural crop production. Compared with traditional pesticides, nanopesticides can interact better with target organisms because of their higher surface area-to-volume ratio. This improved efficiency means that lower doses of nanopesticides can provide the same or better results with the use of fewer active components, reducing environmental contamination and enabling multiple modes of action simultaneously ^[30, 66]. Nanopesticides also increase the stability of the active ingredients, safeguarding them from degradation and ensuring more constant and sustained release in the agricultural field ^[107, 65]. This reduces the need for multiple applications of nanopesticides and lowers environmental exposure. Nanopesticides reduces the effect on nontarget organisms, including beneficial insects and microorganisms, by more accurately targeting pests ^[67]. This characteristic further lowers the overall toxicity of the ecosystem and protects the ecosystem and human health. Nanopesticides offer economic benefits to farmers and the agricultural sector by increasing agricultural yield and quality ^[20].

Mechanism of Action of Nanopesticides

NPs can increase the solubility of weakly water-soluble pesticides, allowing them to be more easily absorbed by pests ^[68]. Nanopesticides are designed to target specific plant tissues or pests and are intended to be more functionally specific by adding molecules (ligands) that attach to specific receptors, proteins, antibodies or peptides on the target pest. This process minimizes the off-target effects of pesticides ^[69, 70, 71]. Compared with traditional pesticides, the smaller size of nanopesticides ensures more effective penetration of biological barriers such as insect cuticles or plant cell walls and their direct delivery to intracellular targets ^[72, 73]. NPs encapsulate active chemicals and protect them from environmental deterioration, allowing them to be released in a regulated and controlled manner ^[74]. Environmental parameters such as pH and temperature stimulate the release of active compounds, ensuring appropriate timing and location ^[75]. Nanopesticides can enter pest cells via endocytosis. Owing to their decreased volatility and solubility, nanopesticides effectively control one of the most critical difficulties associated with traditional pesticides: drift and leaching. Some nanopesticides are also designed to break down into nontoxic byproducts after the active ingredients are released ^[76]. Synergists and adjuvants are frequently added to nanopesticides to improve their overall pesticidal effects and the quantity of target organisms ^[77].

Formulations of nanopesticides

Crop protection employs a range of nanoformulations, which include nanoinsecticides, nanoherbicides, nanofungicides, and nanonematicides^[78]. These nanopesticides are developed to fulfill specific user requirements, such as enhancing solubility, prolonging the release of active ingredients, and preventing degradation. Various modifications and changes to the chemical structure of the carrier molecule are utilized to achieve these objectives, leading to the creation of organic-polymer-based formulations, lipid-based formulations, clay-based nanomaterials, and nanosized metals and metal oxides^[79].

Some examples of these nano formulations include

Nanoemulsion

Oil-in-water nanoemulsion is the term that best describes oil-in-water emulsions because, in this type of emulsion, the surfactant molecules are situated at the interface between the water and the active component and are in the form of nanodroplets in the water. Oil-water nanoemulsion are further subdivided into two categories depending on the amount and category of surfactant used: kinetic stability, and thermodynamic stability^[80]. The thermodynamically stable type refers to a pesticide that is moderately soluble in the aqueous phase and can spontaneously self-assemble into a mixture of surfactant, pesticide and water to form a nanoemulsion-like emulsion. The kinetically stable emulsions remain persistent when external processes cause the active ingredient to dissolve in an emulsion consisting of only the pesticide, so that the emulsion will usually never form. An oil-in-water nanoemulsion of neem oil has been formulated for insect pests^[81].

Nanosuspensions

Commonly referred to as nano dispersions or nanosuspensions, these products consist of pesticides formulated as solid particles at the nanometer scale that are dispersed in water. In these nanodispersions, the surfactant molecules are located at the surface of the particles, with their polar parts extending into the aqueous solution and their nonpolar parts interacting with the solid pesticide^[79]. Some well-known examples of these nanosuspensions are aqueous dispersions of β -cypermethrin, novaluron and nano permethrin^[30]. These compounds are a group of pyrethroid compounds that are used to control pests in sanitation. These are known for their fast-acting effects, high lethality, and long-lasting persistence. It is used in orchards to control the oriental fruit fly, a pest that causes significant economic losses in the fruit and vegetable industry^[82, 83].

Polymer-based nanoparticles

This category of nanocarrier pesticide is primarily used for carrying and targeting active ingredients for slow and controlled release. Additionally, they may also promote dispersion in water and act as a protective reservoir^[84]. Among them are nanoencapsulation, nanospheres, nanogels, nanofibers, etc.

Nanoencapsulation

A nanocapsule is a kind of drug delivery system, specifically a nanoparticle created through nanoencapsulation, which features a clearly defined core that holds either a hydrophobic or hydrophilic active substance and is surrounded by a membrane or polymer. This formulation may help to protect the active ingredients

of the neem-azadiractin formulation during encapsulation^[85]. Some examples of controlled release formulations have been developed for neonicotinoid insecticides, such as acetamiprid and imidacloprid. Acetamiprid is used to control sucking and chewing pests such as aphids and is effective against Hemiptera, Thysanoptera, and Lepidoptera. It is used on a variety of crops, including cotton, chili, okra, green gram, mustard, tea, and many vegetable crops^[86].

Nanospheres

These are spherical structures with a uniform composition where the active component is evenly distributed within the polymer matrix. Example: Nanoparticles of bifenthrin are encapsulated within the polymer in the form of nanospheres. Bifenthrin is useful for controlling insect pests in apples, bananas, pears and ornamentals^[87].

Nanogels

Are also called hydrogel nanoparticles. They are manufactured by cross-linking polymeric particles that have a hydrophilic moiety and hence retain more water. One of the best examples of this is the chitosan nanogel. It serves as a powerful biocidal agent against a range of fungal infections, including Fusarium wilt and head blight in chickpeas and wheat, leaf blast in rice, stalk rot and leaf spot in maize, and blast in finger millet^[88].

Nanofibers

These nanofibers are prepared through electrospinning and thermally induced phase separation of a polymer matrix. Researchers have fabricated electrospun nanofibers that contain (Z)-9-dodecenyl acetate as an active ingredient for the management of lepidopteran insect pests. It is one of the important ingredients of pheromones^[89].

In addition to the previously mentioned formulations, solid nanoparticles are utilized as nanopesticides. Inert dust, such as silica, alumina, and clays, inflicts damage on the waxy layer of insect cuticles through sorption and abrasion. This physical damage can lead to fluid loss in insects, ultimately resulting in dehydration and death^[90, 91]. Nanosilica particles serve an important function in improving plant resilience against both biotic and abiotic stresses. However, excessive amounts of these nanoparticles can adversely affect the properties of grains. Alumina nanostructures also possess pesticidal characteristics. Among metals, the nanoparticles that are most commonly chosen include silver, titanium oxide, copper, cerium, manganese, calcium, and iron^[92]. Silver nanoparticles are favored for their bactericidal, fungicidal, and viricidal capabilities, as well as their low toxicity, inherent charge, extensive surface area, and unique crystallographic structure^[93, 94]. Zinc oxide possesses both antibacterial and antifungal properties, making it ideal for use in agriculture and the food sector^[95]. Titanium dioxide also exhibits strong antimicrobial and antifungal traits. Nano copper damages the cell walls of bacteria and proves effective against bacterial blight at low concentrations^[96].

Conclusions and future aspects

Advancements in nanotechnology and biotechnology have the potential to transform agriculture. These together can address the need for food availability for rapidly growing populations and be helpful in environmental management, especially in developing countries. Compared with their

bulk analogs, nanoparticles have altered physical and chemical properties and have greater applications in agriculture and other fields. Nanopesticide-based formulations are significantly safer and more efficient in terms of promoting sustainable agriculture. At present, in the manufacturing of more environmentally friendly nanopesticide formulations, the development of new targeted delivery systems is an important area of investigation. Furthermore, the use of nanoparticles as active ingredients of nanopesticides will solve several practical issues, such as water solubility and plant resistance. Nanoparticle-based formulations have the ability to increase water solubility, protect active components from untimely degradation, extend pesticide distribution, enhance uptake by the choice of organisms, require small dosages due to meticulous release upon receiving proper stimuli, improve surface properties, such as leaf adhesion and penetration, reduce pesticide losses through leaching and runoff, and auto decay pesticide nanocarriers.

Most of the research on nanoparticles is restricted to the use of nanotechnology in the pharmaceutical industry. For the development of less hazardous and eco-friendly pesticides, there is considerable potential for nanotechnology in the development of nanopesticides for plant defense and new distribution systems. However, despite the several advantages that nanopesticides possess, some drawbacks also exist. These includes low selective toxicity, low biodegradability and the development of resistance against them in targeted and non-target organisms due to their

indiscriminate uses. Moreover, information regarding the environmental behavior of these nanoparticles and their possible harmful impacts on nontarget organisms is scarce, and there is a lack of comprehensive understanding in this domain. It is essential to focus on grasping the possible effects and adverse outcomes of nanoparticles on the environment, non-target organisms, human well-being, and the development of more ecologically friendly nanopesticides.

Future studies should concentrate on creating advanced nanopesticide formulations to address the shortcomings of traditional ones. Innovative technologies that promote environmentally friendly nanopesticide production through green chemistry need to be developed. Efforts should be made to establish methods that lessen the overall expenses associated with nanopesticide formulations. It is important to evaluate the practical effectiveness of nanopesticides in real-world agricultural conditions compared to their chemical counterparts. An assessment of the ecotoxicological impacts of nanopesticides is essential. Furthermore, it is crucial to create legislative and regulatory frameworks to ensure the safe introduction, application, and dosage of nanopesticides in agriculture and other relevant sectors.

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Table 1: List of various types of nano-fertilizers used in agriculture.

Name of Ingredients	Nature of nanoparticles	Target organism	Effect	Reference
Nano-diethylphenylacetamide (DEPA)	Synthesized	<i>Culex tritaeniorhynchus</i> Adult	Nano DEPA exerted better bio efficacy as comparative to its bulk form even at minimal exposure concentrations	[97]
Avermectin	Synthetic	<i>Martianus dermestoides</i> Adult	Higher level of toxicity even at 50%	[98]
Nano-Imidacloprid	Synthetic	<i>M. dermestoides</i> Adult	Higher level of toxicity even at 50%	[99]
Nanopermethrin	Synthetic	<i>C. quinquefasciatus</i> Larvae	More effective at lower concentrations	[100]
Temephos, Imidacloprid	Synthetic	<i>C. quinquefasciatus</i> Larvae	Higher mortality rates even at low concentrations	[101]
<i>Azadirachta indica</i> Neem gum nano formulation	Plant	<i>Helicoverpa armigera</i> <i>Spodoptera litura</i>	Altered activities of detoxifying enzymes carboxylesterases, glucosidases and glutathione S-transferases in the larval gut.	[102]
<i>Artemisia arborescens</i> (Oil)	Plant	<i>Bemisia tabaci</i> Adult	More stability for longer duration	[103]
<i>Bacillus sphaericus</i>	Microbial	<i>Culex quinquefasciatus</i> Larvae	High residual activity, high protection against UV-B radiation and shelf life	[104]
ZnO NPS coated with <i>Bacillus thuringiensis</i>	Microbial	<i>C. maculates</i>	Decrease fecundity, midgut amylase, and GST activity	[105]
Ag NPS	Synthetic, Carrier-free NPs	<i>Bombyx mori</i>	Induce cell necrosis and signal transduction was affected	[106]
Ag NPS	Synthetic, Carrier-free NPs	<i>Drosophila</i>	Depigmentation, impaired movement, compromised fertility, accumulation of ROS and DNA damage	[128]
Ag NPS	Synthetic, Carrier-free NPs	<i>Helicoverpa armigera</i>	Inhibition of gut protease enzyme activity	[108]
Ag NPS	Synthetic, Carrier-free NPs	<i>Spodoptera litura</i>	Accumulation of carboxylesterase in the midgut	[109]
Au NPS	Synthetic	<i>Drosophila</i>	Distributed in the reproductive and digestive enzyme	[110]
Silica NPS	Synthetic	<i>Callosobruchus maculates</i>	Abrasion of insect cuticle and sorption, retarded growth and reduced oviposition	[111]
Mesoporous silica nanoparticles (MSN)	Mildamine	<i>Cucumis sativus</i>	Easily absorbed and transmitted by cucumber plant	[112]

PRO@DMON-GA-Fe(III)	Prochloraz	Rice	Better fungicidal activity against <i>Magnaporthe oryzae</i> with longer duration	[113]
Pro@HMS-TA-Cu	Prochloraz	Oilseed rape leaves	Better antifungal activity against <i>Sclerotinia sclerotiorum</i> and lower toxicity against zebrafish compared with prochloraz technical	[114]
Nano-AVM-GO	Avermectin	Diamondback moth	Better insecticidal effect	[115]
AM@CuBTC	Avermectin	Pine wilt disease	Improved solubility, photolysis performance, and pesticide efficacy	[116]
IV-Porphyrin-MOFs	Tebuconazole	Pathogenic microbes	Good fungicidal effect	[117]
PRCRC	Chlorpyrifos	Tick	Excellent pH sensitivity and excellent insecticidal performance	[118]
MSN	Zobactamide	Phomopsis asparagi	Good bacteriostatic effect	[119]
AL/PEG-acetamiprid	Acetamiprid	<i>Xanthogaleruca luteola</i>	Increased insecticidal performance	[120]
SPc-calcium glycine	Calcium glycine	Tomato mosaic virus	Improved control of virus	[121]
SPc-dinotefuran	Dinotefuran	Aphids	Better distribution and enhanced uptake	[122]
SPc-chitosan	Chitosan	<i>Phytophthora infestans</i>	Enhanced control effect	[123]
Nanoindoxacarb	-	<i>Bemisia tabaci</i> Silverleaf whitefly	Reduced cost of insecticide application and less leaching in water table	[124]
Nanoindoxacarb	-	<i>Spodoptera littoralis</i> cotton leafworm larvae	reduce the environment contamination, control cost and pest population.	[125]
Nano Silver liquid	Synthetic	<i>Sclerotium cepivorum</i> White rot of Onion	increased biomass and dry weights of crop and minimal changes in soil composition	[126]
Nano-pyrifluquinazon	Chitosan	<i>Myzus persicae</i> Green peach aphid	Insect rapidly stopping feeding and starves to death	[127]

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