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Role of metallic nanoparticles in the control of hazardous insects affecting plants and animals

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Abstract

The necessity for more agricultural production can be fulfilled by increasing crop productivity because the cultivated area is constrained. The main source of food and nutrients for domestic animals and humans comes directly or indirectly from agriculture. However, along with climate change, plant diseases, pests, poor soil health, weeds, natural disasters, and reduced nutrient availability, all contribute to a large loss of worldwide crop production under current farming practices. According to the latest studies, insects account for almost 20-40% of all yield losses in agriculture each year, with acute infestations causing even more harm in some areas. One of the main concerns for international food security is the financial burden of controlling these pests, both in terms of direct output losses and the expenses related to pest control procedures. Application of pesticides on the farm poses a variety of challenges for farmers, who must decide which pesticides to use for a given pest as well as when and how to apply them. Nanotechnology has been widely used in agriculture to boost the production of crops through a variety of methods, including control of pests, seed treatment, enhancement of the germination process, nutrient balance, and improved fertilizer delivery. In this review, the role of metallic nanoparticles (MNPs) against hazardous insects (pests) in their control and the mechanism of actions of MNPs have been summarized.

1. Introduction

The economy of any nation is strengthened by agricultural and livestock production, which is essential for meeting both the needs of living and the need for raw materials by industry. Higher food output is necessary due to the ongoing growth of the human population, which is expected to reach 10 billion by 2050. The need for more agricultural production can be met by increasing crop productivity because the cultivated area is constrained. The main source of food and nourishment for domestic animals and humans comes from agriculture, however, by 2050, it is expected that food demand will have increased by 70% (Abdel-Aziz et al. 2019). While high yields in agriculture are crucial for sustainability, they also have detrimental effects on the environment due to water use, ecosystem degradation, and the applications of agrochemicals on the soil (Shekhar et al. 2021). Among the tactics of sustainable agriculture techniques are the rotation of crops, integrated pest management systems, mechanical or biological control of weeds, and pesticide reduction (Kannan et al. 2023). However, in addition to climate change, plant diseases, weeds, pests, poor soil health, natural disasters, and decreased nutrient availability all contribute to a large loss of worldwide crop production under current farming systems (Mittal et al. 2020).

By feeding directly on plants and damaging essential components like the leaves, stems, and fruit, insect pests significantly lower crop output. Damage from their eating can take several forms, ranging from leaf defoliation and stunted development to total crop destruction. Locusts, aphids, moth larvae, and beetles are some of the most destructive pests that may quickly decimate enormous agricultural areas (Sharma et al. 2017). Staple crops like maize and rice are severely harmed by the Fall Armyworm (*Spodoptera frugiperda*), which has advanced over Africa, Asia, and Latin America. Research indicates that African farmers lose over $13 billion a year due to this bug alone (Mendesil et al. 2023). Insect pests have a stunning cumulative impact on agriculture worldwide. According to studies, insects account for 20–40% of all losses in agriculture each year, with severe infestations causing even more harm in some areas (Tonnag et al. 2022).

By employing a controlled release technique with active compounds that are nanoscale encapsulated, new technologies can lessen the negative impacts of pesticides (de Albuquerque et al. 2021). The active ingredients in nano pesticides thus can be uniquely formulated at the nanoscale to enhance delivery and efficacy, improving dispersion stability, producing formulations with controlled or gradual release, and offering more control in field applications

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(Grillo et al. 2021). Numerous advantages of nano pesticides include increased potency and durability as well as fewer active ingredients, which opens up a variety of efficient ways to lessen the ecological damage that chemical pesticides do (Awad et al. 2022). This review article aims to explore the potential of metallic nanoparticles (MNPs) as effective alternatives to control hazardous insects affecting both plants and animals. Additionally, this review also addresses the challenges, and safety measures for the application of MNPs in integrated pest management strategies.

2. Global food security

One of the biggest concerns for international food stability is the financial burden of controlling these pests, both in terms of direct output losses and the expenses related to pest control procedures (Skendžić et al. 2021). Impulsive crises in the agriculture sector frequently impact food stability. The majority of these nutritional crises are caused by significant plant disease epidemics, with arthropod pests serving as the major causative agents (Jarmul et al. 2020). Because they consume leaves, stems, fruits, and roots, plant insects directly harm crops. Lower yields, stunted development, and decreased photosynthesis are the consequent outcomes (KhokharVoytas et al. 2023). In many regions of the world, staple crops including wheat, maize, rice, and cotton are notoriously destroyed by major pests like aphids, whiteflies, and different beetle species (Hajjar et al. 2023). The financial toll of pest infestations is enormous; estimates indicate that pest infestations by insects account for 10–15% of all agricultural losses worldwide each year, or billions of dollars (Oyediran 2023). For example, a significant insect pest of cotton and a number of other crops is the cotton bollworm, *Helicoverpa armigera*. Significant economic losses result from the severe damage caused by its larval stages (Bessembayeva et al. 2024). It has been estimated that *H. armigera* causes cotton losses in India of more than $500 million a year (Belagalla et al. 2024). Due to its destructive nature, farmers are now more dependent on chemical-based pesticides, which increases production costs and presents environmental risks. Many plant insects not only cause direct harm but also operate as carriers of bacterial, fungal, and viral infections that have a major effect on agricultural output. Aphids, for instance, are carriers of over 100 plant viruses, such as the commercially significant barley yellow dwarf virus (BYDV), which lowers cereal crop yields globally (Khan et al. 2023a). Whiteflies spread viruses like the cassava mosaic virus and the tomato yellow leaf curl virus (TYLCV), which cause large crop losses in Asia and Africa (Soumia et al. 2021). The financial costs brought on by these illnesses can greatly outweigh the harm that direct feeding causes (Tatineni and Hein 2023).

Food security is directly threatened by the rising incidence of plant-insect pests, especially in areas where famine and malnutrition already exist. Because insects can destroy staple crops, low-income populations may experience food shortages, price increases, and limited access to food. An estimated 821 million people experience food insecurity globally, according to the United Nations Food and Agriculture Organization (FAO), and one of the main causes of this problem is the destruction done by plant insect pests (Abdolkhani and Mohammadi 2023). By changing both the distribution and the actions of pest species, climate change is making plant insects an even greater hazard. Increased CO_2 altered precipitation patterns, and rising temperatures can all make insect outbreaks more likely. Insects can spread out geographically, reproduce more quickly, and endure winters that would typically restrict their numbers (Kaur et al. 2023).

3. Traditional techniques for insect pest management

Currently, over 450 active ingredients are authorized for use in pesticides, and over 333,000 tons are marketed annually throughout the EU (as of 2021) (Schleiffer and Speiser 2022). All things considered, the United States consumed the most pesticides in the world in 2020, using about 407.8 thousand metric tons, followed by Brazil, which consumed 377.2 thousand metric tons in that year. In 2020, 2.66 million metric tons of pesticides were consumed worldwide. The amount of pesticides used in farming operations increased by more than 50% worldwide between 1990 and 2010. Nonetheless, consumption has stayed mostly constant since then, declining a little from 2.68 million metric tons in 2011 to 2.66 million metric tons in 2020 (Daraban et al. 2023; Yessenbayeva et al. 2024). Rachel Carson made the public aware of the problems that might arise from the careless use of pesticides in 1962 with the publication of her book Silent Spring. This book raised serious worries about the effects of pesticides on the environment and human health (Hellou et al. 2013).

The majority of national and intergovernmental bodies firmly believe that the next officially recognized framework for evaluating crop protection will be Integrated Pest Management (IPM). As a result, all EU farmers have been required to follow the general guidelines of Integrated Pest Management (IPM) since 2014. IPM is defined in the majority of guidance publications as a methodical and comprehensive "approach" or "strategy" for managing plant pests while minimizing the use of synthetic pesticide (Nadi et al. 2024; Pazla et al. 2024). The goal of IPM is to efficiently manage pests while preventing their populations from reaching economically detrimental levels, rather than eradicating them. By putting this plan into practice, farmers, consumers, and the environment will be exposed to less toxicity, and the damage caused by pesticide-resistant pests will be reduced (Stenberg 2017). Depending on their intended application, pesticides are also known as insecticides, herbicides, fungicides, rodent killers, molluscicides, nematicides, and acaricides (Daraban et al. 2023). Benzoic acids, triazines, phenoxy acetic acid derivatives, carbamates, organochlorides, pyrethrins and pyrethroids, organophosphorus, dipyridyl derivatives, glycine derivatives, and dithiocarbonates are among the pesticides that can be categorized based on their chemical structure (Bortoli and Coumoul 2018) as illustrated in Fig. 1.

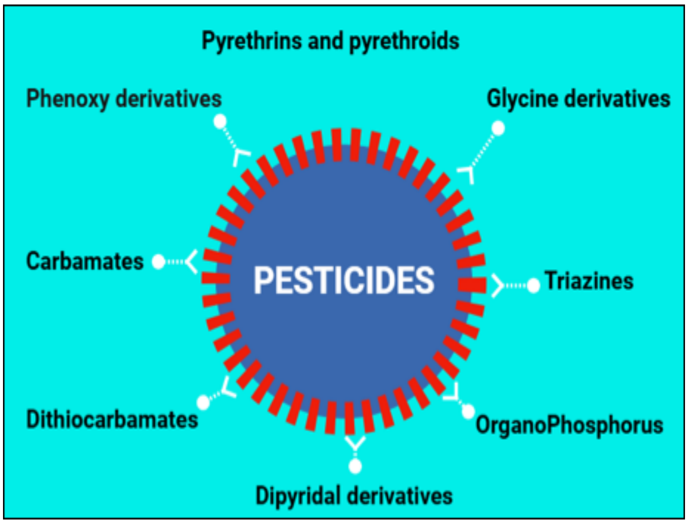

***Fig. 1**: Schematic diagram representing main classes of pesticides (www.biorender.com)*

4. Pesticide toxicity and their effects on the environment, animals, and human health

Pesticides, though crucial for managing pests, pose significant risks to animal health. Animals can be exposed through inhalation, skin contact, or ingestion, which may result in symptoms like drooling, skin rashes, vomiting, diarrhea, or, in extreme situations, seizures and severe lethargy (Khan et al. 2023a). Certain types, such as organophosphates, are especially harmful as they disrupt the activity of acetylcholinesterase, a vital enzyme for nerve functioning, leading to neurological issues. Research indicates that even minimal exposure can lead to reproductive challenges and developmental problems in offspring. Moreover, pesticides such as cypermethrin have been associated with adverse effects on the male reproductive system in laboratory animals, including reduced testosterone levels, changes in sperm production, and structural damage to reproductive tissues (Yadav et al. 2024). Pesticides can also indirectly damage ecosystems by affecting animal behaviors crucial for survival. For example, exposure to chlorpyrifos in tadpoles has been shown to interfere with survival instincts, potentially causing population reductions (Poliserpi and Brodeur 2023).

Employing pesticides on the farm presents a variety of challenges for farmers, who must decide which pesticides to use for a given pest/s, as well as when and how to apply them. Overuse of pesticides typically results in higher expenses and lower earnings for farmers in addition to the risk to the ecosystem and/or public health. Beneficial creatures and biodiversity can flourish when minimal pesticide applications and lower amounts of active chemicals (pounds or kilograms) are used, reducing the strain on non-target organisms (Daraban et al. 2023). This is why, although it is the most widely used metric, "pounds/kilograms of active ingredient applied" is not a comprehensive measure of changes in pesticide use. This measure does not take into consideration variations in target pests, application techniques, or pesticide toxicity (Benbrook and Benbrook 2021). Eighteen variables in the pesticide usage Minimum Dataset (MDS), created by the Heartland Health Research Alliance (HHRA), combine to provide fundamental information about shifts in pesticide use (Daraban et al. 2023). Although application rates have generally declined, the quantity applied has stayed largely constant. Certain pesticides, for instance, are administered at high rates/acre, and sometimes even over 100 pounds, while other pesticides that serve a similar purpose, or occasionally even better, may be treated at much lower rates per acre (Daraban et al. 2023).

Despite their advantages in agriculture, pesticides have been shown to be harmful to both humans and the environment. Many of these high-toxicity substances are prone to bioaccumulation and remain persistent in the environment. However, according to estimates, less than 1% of the entire amount of pesticides used to eradicate weeds and other pests actually reach the intended pests (Barzman et al. 2015). Pesticides enter the environment during the treatment formulation and application stages. Various spraying procedures may be used depending on the composition type, intended pest, and application schedule. Boom sprayers, burrow sprayers, and aerial applications are commonly used to apply liquid sprays to crops. Pesticides can be sprayed on the surface of the ground, injected as fumigants, or administered as granules, depending on the kind of soil. Eventually, the pesticides will be incorporated into the topsoil. Furthermore, herbicides are frequently applied to seeds prior to seeding (Tudi et al. 2021). Pesticides may reach surface water bodies, volatilize into the surrounding environment, or enter non-target organisms by ingestion. Following treatment, they are likely to be consumed by target organisms, decompose, or move to groundwater. The physical and chemical characteristics of pesticides, the soil, geographical conditions, and management techniques all directly influence their behavior and destiny (Rasool et al. 2022). A significant amount of active pesticide ingredients frequently persists in the soil, where they undergo biochemical changes that affect the soil's microbial and enzymatic activity. It is challenging to evaluate enzymatic and microbiological reactions after pesticide application because of the structural diversity and variety of breakdown pathways of synthetic pesticides (Wołejko et al. 2020).

5. Effect of pests on feed and fodder of Animals

Pests severely impact the quality and availability of feed and fodder crops for livestock impacting nutrition, productivity, and economic value of farm animals. Insect pests, weeds, and many fungal pathogens disrupt various stages of fodder crops which ultimately results in the loss of net yield, nutrition depletion, and contamination (Belehegn et al. 2020). For instance, locust swarms (*Schistocerca gregaria*) devastate pastures and fodder crops in semi-arid regions, consuming up to 80–100% of vegetation during outbreaks (Ayana 2023). A 2020 FAO report highlighted that locust invasions in East Africa (Kenya, Ethiopia, Somalia) destroyed over 1.8 million hectares of grazing land, slashing fodder availability by 70–90% in affected areas and threatening the livelihoods of 20 million pastoralists (Simpkin et al. 2020). Similarly, the fall army worm (*Spodoptera frugiperda*), introduced to Africa in 2016, has caused 40–60% yield losses in maize which is a critical fodder crop across 28 countries, including Zambia and Malawi, where smallholder farmers rely on maize stover for cattle feed (Otim et al. 2021; Haryati et al. 2025). Stem borers (*Busseola fusca* and *Chilo partellus*) reduce sorghum and millet yields by 20-40% in sub-Saharan Africa (Nigeria, Sudan), directly affecting fodder reserves during dry seasons (Binjamin et al. 2024).

Invasive weeds like *Parthenium hysterophorus* (congress grass) outcompete native fodder species, reducing biomass by 50–70% in South Asia (India, Pakistan) (Shabbir et al. 2024). A 2019 study in *Crop Protection* noted that *Parthenium* infestations in Punjab, India, lowered green fodder production by 1.2–1.8 tons/hectare annually, forcing farmers to rely on expensive alternatives (Mashandete et al. 2010). Fungal pathogens, such as *Aspergillus flavus*, produce aflatoxins in stored fodder, contaminating 30-50% of silage in tropical regions (Brazil, Southeast Asia), Aflatoxin-contaminated feed not only reduces palatability but also causes liver damage and immunosuppression in livestock, exacerbating losses (Jiang et al. 2021). Termites (*Odontotermes spp.*) damage dry fodder stores in arid zones, destroying 30-50% of stored crop residues in Rajasthan, India (Kumar 2018).

Climate change exacerbates pest-related losses by expanding pest habitats. For example, warmer temperatures have enabled the Mexican bean beetle (*Epilachna varivestis*) to infest soybean fodder in Central Mexico, causing 40–70% defoliation (Munaiz 2018). Aphids (*Aphis craccivora*) and whiteflies (*Bemisia tabaci*) transmit viral diseases in leguminous fodder crops like alfalfa and cowpea, reducing yields by 30-60% in the U.S. Midwest and Australia's Murray-Darling Basin (Nair et al. 2018). A research study found that aphid infestations in Australian lucerne fields lowered crude protein content by 15–25%, compromising feed quality (Lan et al. 2024). The economic ramifications were severe in East Africa, where locust-related fodder shortages increased feed costs by 300-400% during the 2019-2021 outbreaks, forcing farmers to sell livestock at reduced prices (Ahmad et al. 2022). In Brazil, *Spodoptera* infestations in maize fodder led to a 12-15% decline in dairy production (Mishra et al. 2024). Integrated pest management (IPM) strategies, such as biopesticides and resistant fodder varieties (e.g., ICAR's *Parthenium*-tolerant sorghum), have reduced losses by 30–50% in pilot regions (Idrees et al. 2021). However, limited adoption due to cost and knowledge gaps persists, particularly in low-income regions. Addressing these challenges requires region-specific pest surveillance, climate-resilient fodder systems, and policies supporting affordable pest control to safeguard global feed security (Heydari et al. 2021).

6. Nanotechnology in agriculture

Precision farming uses nanotechnology to increase crop productivity and regulate target activity according to environmental variables (Chhipa 2017; Mustafa et al. 2024). Nanotechnology has been widely used in agriculture to boost crop yields through a variety of methods, including control of pests, seed treatment, enhancement of germination process, nutrient balancing, improved fertilizer delivery process, gene transfer, identification and elimination of toxic agrochemicals, nano-sensors for pathogen detection, and nano filters for water purification (Bahrulolum et al. 2021). Fig. 2 illustrates several uses of nanotechnology in crop protection and agriculture. The extensive application of nanotechnology in agriculture and livestock is a result of the special properties of nanomaterials, including their small size (1 to100 nm), huge surface area, enhanced permeability, thermal stability, dispersion, and biodegradability (Athanassiou et al. 2018; Azam et al. 2023). Because of their unique characteristics, nanomaterials are considered to be efficient carriers for stabilizing fertilizers and insecticides. They are also useful for facilitating controlled nutrient transfer and improving crop protection (Bahrulolum et al. 2021). Due to their property of being absorbed quickly and precise nutrient distribution in plants, nano fertilizers are superior to conventional fertilizers (Abdelmigid et al. 2022; Silvera-peblo et al. 2024). It increases plant roots' capacity to absorb nutrients, which improves crop yield and the process of photosynthesis (Zulfiqar et al. 2019). Numerous studies have shown the significance of NPs as nutrient transporters in crop development. Cota-Ruiz et al. (2020) examined copper NPs that are used as fertilizers for alfalfa (*Medicago sativa*) plants and found that nano-copper improved the micronutrient value and physiology of the plants. It was discovered that using zinc oxide NPs as a nano fertilizer improved the yield and nutritional value of soybeans (*Glycine max*) cultivated on soil lacking zinc (Yusefi-Tanha et al. 2020; Naeem et al. 2023). In recent findings application of silver NPs (Ag NPs) was carried out to check the acaricidal activity against *Hyalomma dromedarii* and efficacy was checked using Adult immersion tests (AITs) and results showed that Ag NPs significantly control ticks (Abdel-Ghany et al. 2022). In some other studies, the use of titanium dioxide nanoparticles (TiO_2 NPs) to check the larvicidal activity against *Rhipicephalus microplus*, *H. anatolicum*, and *Haemaphysalis bispinosa* were investigated and results showed that NPs that were of 30 nm in size exhibited significant larvicidal activity by damaging their cellular structure (Rajakumar et al. 2015).

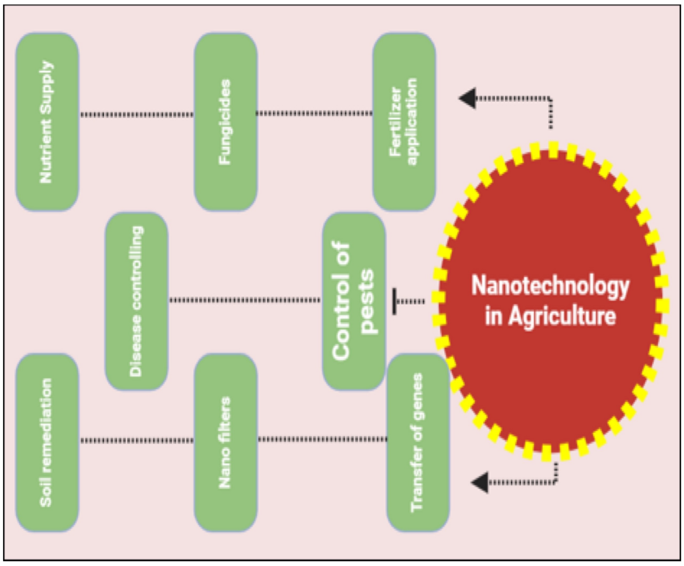

Fig. 2: *Areas of Nanotechnology in Agriculture (www.biorender.com)*

7. Criteria for choosing nanoparticles

Generally speaking, important characteristics like affordability, nontoxicity, biocompatibility, and biodegradability are taken into consideration when choosing materials for agricultural uses (Pandey 2018; Khan et al., 2023e). Varied nanocarriers are needed because of their varied targets, which include viruses, fungi, weeds, crops, and pest species. This implies that the targets' physiological and physicochemical needs must be met by the nanocarriers (Li et al. 2021). Crop quality and production, economic performance, environmental compatibility, nutrient loading capacity, nutrient release rate, and nutrient usage efficiency are the main considerations when selecting nanostructured materials for fertilizer delivery (Guo et al. 2018). Because of the intricate structure of the plant cell wall, choosing penetrating nanocarriers requires careful consideration of factors like size, shape, and surface properties (Li et al. 2021). For example, chitosan nanoparticle-controlled release matrices exhibiting antibacterial properties are thought to be novel approaches to microbial control (Mujtaba et al. 2020). Particles made of metals or metal compounds having at least a dimension between 1 and 100 nanometers are known as metallic NPs. Due to their unique biological, chemical, and physical properties, NPs have gained much attention in modern times (Masarovicova and Králová 2013; Asghar et al. 2024). Their small size, high surface area-to-volume ratio, and quantum effects make them extremely adaptable for various applications in fields such as electronics, environmental remediation, medicine, and catalysis (Khan et al., 2023b; Ryandini et al. 2024). Despite their apparent benefits in the biomedical field, MNPs nevertheless have some drawbacks, including unequal bio-distribution, a tendency to silt and aggregate, clearance by macrophages, and undesired interactions with biologically viable tissues (Canaparo et al. 2020). Researchers have worked to overcome these bottlenecks by surface-functionalizing or conjugating them with natural polymers or molecules to make them stable and covert in physiological media, reducing their negative effects and increasing their effectiveness and biosafety (Hassan et al. 2021).

Reducing or capping agents are usually needed to synthesize or stabilize MNPs by chemical techniques, which have been used extensively. One of the most popular chemical processes for creating MNPs is photochemical synthesis, followed by Sono-chemical and

Table 1 Thorough analysis of the benefits and drawbacks of the most popular synthesis techniques of metallic nanoparticles

Method of synthesis	Examples of synthesised MNPs	Advantages	Disadvantages	Reference
Ball milling	CuO NPs TiO_2 NPs Ag NPs ZnO NPs	1.Well controlled 2.Simple 3.Scalable	1.Require high energy 2.Milling media affects the final purity and microstructure of metallic nanoparticles 3.Very time consuming	(Sidiqi et al. 2024)
Mechano-Chemical method	Ag NPs Fe_2O3 NPs	1.Fast and very simple 2.Very efficient 3.Product of tunable morphology	1.Take a lot of time 2.Not applicable for all NPs 3.Only for the NPs less than 20 nm in size	(Khayati et al. 2013)
Laser irradiation method	ZnO NPs TiO_2 NPs Fe_3O_4 NPs Ag NPs Au NPs CuO NPs	1.No energy waste in the form of heat 2.Takes only one step for the synthesis 3.Product of tunable morphology 4.Simple and effective 5.Yield high amount of NPs	1.Its probe blocks the pathway and obstructs the energy of the laser by the high amount of formation of NPs 2.It reduces further rate of ablation	(Iravani et al. 2014; Iqbal et al. 2024)
In situ reduction	Au NPs	1.Formation of NPs in an easy way by simple physical and chemical methods 2.Needs no extra linker	1.High impurity risk and cause toxicity 2.High cost and poor reducing capability 3. It makes controlling overall properties of synthesized NPs difficult	(Chen et al. 2020; Altaf et al. 2024)
Bath deposition by chemical	Palladium Sulphide NPs Cd Sulphide NPs Fe NPs ZnO_2 NPs	1.No need of any pressure or temperature 2.Very simple and eco-friendly 3.Product of tunable morphology 4.Faster compared to hydrothermal method	1.High wastage of precursor solution 2.Precursor must be clean in this method	(Rosli et al. 2023)
Co-precipitation	Fe_3O_4 NPs Fe-doped CeO_2 NPs	1.High throughput 2.Scalability 3.High throughput	1.Difficulty in handling 2.Possibility of surface oxidation	(Sodipo et al. 2023)
Chemical precipitation	ZnO NPs doped with Ag CuO NPs CdO NPs doped with Ag	1.Scalability 2.High speed	1.Difficult in handling the structural attributes	(Sagadevan et al. 2017)
Sol-gel method	ZnO_2 NPs TiO_2 NPs	1.Scalability	1.Difficulty of producing porous films	(Hasnidawani et al. 2016)
Hydrothermal method	Fe NPs ZnO_2 NPs	1.High efficiency 2.Narrow size 3.Product distribution 4.Morphology can be controlled very easily even at large scale	1.Need of high temperature 2.Time consuming 3.Probable degradation of thermos labile drugs	(Shibeshi et al. 2022)
Electro-deposition	Ni NPs TiO_2 NPs Ag NPs Au NPs	1.Fast and robust 2.Cost-effective 3.Product of tunable morphology	1.Not applicable for production on a large scale 2.Having multiple steps and time consuming	(Mohanty 2011)
Microemulsion synthesis	Organometallic in addition to unusual nanostructured inorganic materials like CuS, $Mo(CO)^6$, $Fe(CO)^5$, $Co(CO)_3NO$	1.Having control over the size and many other physical aspects of the NPs 2.No need of reduce agents	1.Need of surfactants	(Munoz-Flores et al. 2011)

microwave processing. But because they are poisonous, these substances are extremely dangerous for both environmental and medical safety. Since bacteria, actinomycetes, viruses, fungi, yeast, or plants can use biosynthetic pathways, this has encouraged the development of green techniques for MNP production (Ehsan et al. 2022). Interestingly, a variety of techniques can be applied to certain synthesis needs (mostly for the synthesis of bimetallic MNPs). These methods need to be adjusted in order to synthesize MNPs with a variety of characteristics, and each has pros and cons of its own (Srinoi et al. 2018).

8. Types of metallic NPs used in pest control

MNPs have shown great promise as a pest management tool because of their special physicochemical characteristics. Because of their ability to kill agricultural pests, several kinds of metallic nanoparticles, including copper (Cu NPs), zinc oxide (ZnO NPs), silver (Ag NPs), and titanium dioxide (TiO_2 NPs), are frequently used (Tortella et al. 2021). The strong antibacterial qualities of silver nanoparticles, which efficiently combat bacteria, fungi, and insect pests, have led to extensive research into these materials. Strong antibacterial and pesticidal qualities are also displayed by ZnO and Cu nanoparticles, which cause cellular membrane disruption and the production of reactive oxygen species, which causes oxidative stress in pests (Jafir et al. 2023). Furthermore, TiO_2 nanoparticles, which are typically employed in photocatalysis, have the ability to break down harmful substances that pests create (Bihal et al. 2023). The eco-friendliness and target-specificity of these NPs enable them to effectively control a wide range of pests while reducing the need for traditional chemical pesticides, which frequently have negative environmental effects. In order to ensure sustainable agricultural practices and improve crop protection, ongoing research attempts to maximize the utilization of MNPs (Lan et al. 2024).

8.1 Silver NPs (Ag NPs)

The strong biocidal activity of Ag NPs is well known, and there are multiple ways in which they affect insects. Ag NPs cause toxicity primarily by entering the insect cells through its cuticle and interfering with regular physiological functions. Once inside, Ag NPs have the ability to bind with DNA and proteins within cells, causing oxidative stress (Nie et al. 2023). Reactive oxygen species (ROS) are produced as a result of this stress, which damages proteins, nucleic acids, and cell membranes, leading to cellular malfunction and eventually cell death (Acar and Özgül 2023). Another explanation is that the insect defense systems are weakened when the action of its enzymes, especially those involved in detoxification, is disrupted. Ag NPs are also known to prevent breeding and feeding, which lowers pest populations even further. Furthermore, the NPs may interfere with the ion channels in insect cells, altering the signals of the nervous system and resulting in paralysis and death (Moraes-de-Souza et al. 2024). One study investigated the larvicidal activity of silver and silver chloride NPs against *R. microplus* larvae and these NPs were synthesized using *Mimosa pudcica* extract and biological assay revealed that a concentration of 8.98 mg/mL showed maximum larvicidal potential (Benelli et al. 2017)

8.2 Efficacy against specific insect pests

The use of NPs designed through various techniques showed promising results against insect pests of plants and animals. Some key NPs that showed better results against targeted insect pests are summarized. Silver NP has been very successful in combating agricultural pests that seriously harm crops, such as *Plutella xylostella*, *Helicoverpa armigera*, and *Spodoptera litura* (Razzaq et al. 2023). According to some recent research when Ag NPs are used as a pest management approach they significantly lower their survival rate by hampering their growth and decreasing their reproductive potential. The potential of Ag NPs in vector control is demonstrated by the fact that, for example, exposure to Ag NPs increased mortality in *Aedes aegypti*, the mosquito that spreads diseases like dengue and Zika (Khan et al. 2023d; Ali et al. 2024). Ag NP treatments have also been successful in controlling *Sitophilus oryzae*, a significant pest of stored grains, by lowering adult emergence and feeding damage. The diverse mechanisms of action of Ag NPs are responsible for their broad-spectrum effectiveness against a variety of insect species, and their environmentally favorable characteristics make them a desirable substitute for traditional chemical insecticides (Khan et al. 2023c).

8.3 Zinc Oxide NPs (ZnO NPs)

Zinc oxide NPs gained attention as pest control agents due to their insecticidal potential and being eco-friendly. These NPs showed insecticidal mechanisms by the production of reactive oxygen species which induce oxidative stress in the cells of insect pests (Gauba et al. 2023). Insects eventually die as a result of cellular malfunction brought on by this oxidative stress, which also destroys proteins, lipids, and nucleic acids. ZnO NPs can also interfere with the insect's ability to absorb nutrients, causing starvation, stunted growth, and decreased reproduction (Wani et al. 2023). ZnO NPs are excellent for application in both field crops and stored products since studies have shown that they are very efficient against a variety of insect pests, such as *Sitophilus oryzae*, *Helicoverpa armigera*, and *Aphis gossypii* (Jafir et al. 2023). The effectiveness of these NPs increased by the strong interaction of NPs with insect tissues due to their small size and large surface area. To prevent insect infestations, ZnO NPs can be incorporated into coatings for grains that have been kept or sprayed on leaves (Abd El-Latef et al. 2023). ZnO NPs are a flexible tool in agricultural pest management because of their UV-blocking qualities, which also serve as an insect deterrent and give crops more protection from UV radiation (Mondéjar-López et al. 2024).

Recent findings highlighted the effectiveness of ZnO NPs in combating ticks and lice, presenting a sustainable alternative for managing these pests in animals. For example, ZnO NPs synthesized using *Momordica charantia* leaf extract have demonstrated notable

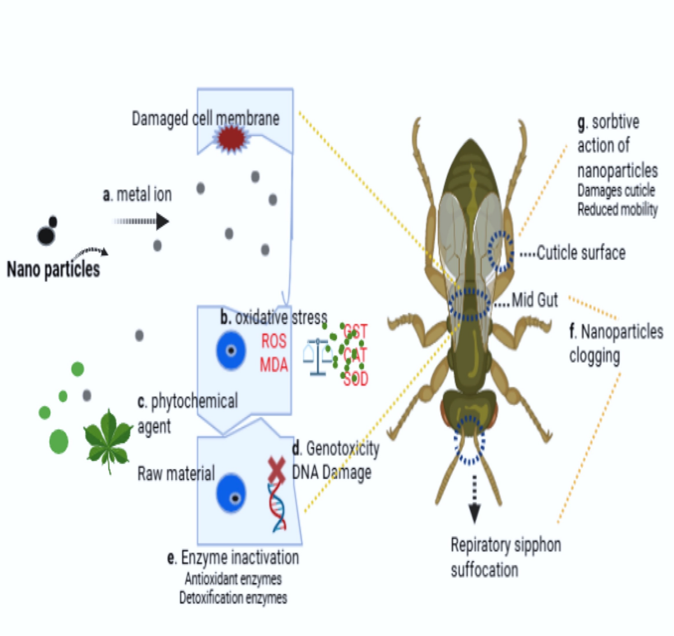

***Fig. 3**: Action mechanism of MNP against insects **a**. metal ions released from NPs alter the cell membrane **b**. MNPs disturb redox balance **c**. phytochemicals in the raw material onset a complex reaction **d.** MNPs can damage the genetic material and cause toxicity **e.** MNPs inactivate many enzymes by detoxifying them or by the production of antioxidant **f.** MNPs clog the midgut and respiratory pathway of insect **g.** MNPs may damage the insect cuticle surface and reduce their motility*

toxicity levels, with LC_{50} values recorded at 6.87 mg/L for *R. microplus* larvae (commonly known as cattle tick) and 14.38 mg/L for adult *Pediculus humanus capitis* (head lice) (Doğaroğlu et al. 2024). Additionally, ZnO NPs produced through wet chemical synthesis methods achieved complete mortality of *R. microplus* larvae within 12 hours and *P. humanus capitis* within 6 hours under specified concentrations. These NPs interfere with vital physiological processes in parasites, ultimately causing their death. While they represent an environmentally friendly solution for pest control, further exploration is necessary to evaluate their broader ecological impacts and ensure safe and practical usage (Abdel-Ghany et al. 2022). Application of Zn NPs on *R. microplus* adults was carried out and NPs were synthesized using *Lobelia leschenaultina* extract and at a concentration of 1.9 mg/mL indicating strong potential to control *R. microplus* infestation (Benelli et al. 2017).

8.3.1 Effect of synergy with other pesticides

Zinc oxide showed better results when used solo but its use with the combination of other traditional insecticides also showed better results in enhancing their mechanism to control pests, for instance when used with traditional insecticides like pyrethroids or organophosphates it lowers the dosage rate while showing better results (Abd El-Latef et al. 2023). Several techniques are used to accomplish this synergistic action, such as ZnO NPs enhancing oxidative stress by producing ROS and improving the accessibility of the insect cuticle, which allows the chemical insecticide to penetrate more easily. A higher insect death rate and a slower pace of pest population resistance development are the outcomes of the combined effects (Jafir et al. 2023).

For example, research has demonstrated that ZnO NPs considerably increase the mortality rates of pests like *Spodoptera litura* and *Tribolium castaneum* when used in conjunction with pesticides like imidacloprid or *Bacillus thuringiensis* (Bt) toxins (Jafir et al. 2023; Abbas et al. 2024). On similar lines, ZnO NPs have demonstrated improved efficacy against pests such as *Aedes aegypti*, a mosquito that transmits several diseases, when combined with natural bio-pesticides like neem oil (Rajput et al. 2023). By reducing the dosage of hazardous pesticides, ZnO NPs' synergistic potential not only increases the effectiveness of pest control but also lessens the environmental impact, promoting more integrated and sustainable pest management techniques (Lan et al. 2024; Aleem et al. 2023).

8.4 Titanium Dioxide NPs (TiO_2NPs)

TiO_2NPs gained attention in pest management due to their photocatalytic characteristics as it produce reactive oxygen species such as super-oxides and hydroxyl radicals when exposed to UV light (Olawade et al. 2024). These ROS are extremely harmful to insects because they induce oxidative stress, which damages proteins, DNA, and cell membranes, ultimately resulting in insect death. Because of their ability to break down organic materials like insect exoskeletons and cuticles and interfere with essential physiological functions in pests, the photocatalytic action of TiO_2 NPs makes them a desirable and environmentally benign choice for pest management (Ragheb et al. 2023). Since light activates their mode of action, TiO_2 NPs, in contrast to conventional pesticides, do not rely on chemical toxicity and can effectively reduce pest populations with little harm to the environment. They can also be used to break down chemical residues in agricultural fields due to their photodegradation properties, providing the twin advantages of environmental rehabilitation and pest management (Shanaah et al. 2023).

8.4.1 Case studies in controlling pests

Numerous case studies have shown how TiO_2 NPs can be effectively used in agriculture to control pests. For example, TiO_2 NPs have been employed in greenhouse settings to reduce cotton aphids (*Aphis gossypii*) and two-spotted spider mites (*Tetranychus urticae*) in crops like cucumbers and tomatoes (Adetuyi et al. 2024). When exposed to UV radiation, TiO_2 NPs, which were sprayed on leaves in these tests, dramatically decreased insect populations without compromising plant growth or yield. In another case study, TiO_2 NPs demonstrated improved stored grain protection against *Sitophilus zeamais* by interfering with insect growth and respiration when exposed to light (Jasrotia et al. 2022). TiO_2 NPs have also been assessed for their use in integrated pest management (IPM) strategies, which combine them with other chemical or biological control techniques to increase overall pest control effectiveness while reducing the usage of pesticides. These case studies highlight the TiO_2 NPs as a light-activated, sustainable pest management tool in agriculture, providing a novel way to lessen reliance on chemical pesticides (Adetuyi et al. 2024). Titanium dioxide NPs were also analyzed to check larvicidal activity against *Hyalomma anatolicum* which were synthesized using an extract of *solanum trilobatum* extract results showed at a concentration of 25.85 mg/mL there is maximum potential for controlling *H. anatolicum* and noticed the reduction of Theileriosis disease which parasitizes the livestock including cattle, goats, and sheep (Al-Salih et al. 2023)

8.5 Copper NPs (Cu NPs)

Because Cu NPs can interfere with a number of insect physiological functions, they have demonstrated significant promise in the management of pests. Cu NPs primarily use the production of reactive oxygen species (ROS) to achieve their insecticidal actions. In insect cells, these ROS induce oxidative stress, which damages essential cellular constituents like proteins, lipids, and DNA (Rai et al. 2018). Cell death results from this oxidative damage because it weakens cellular membranes and interferes with metabolic functions. Furthermore, Cu NPs exacerbate oxidative stress in insects by interfering with the activity of detoxifying enzymes like catalase and superoxide dismutase (Pramanik et al. 2023). Additionally, Cu NPs have the ability to attach to proteins and enzymes, interfering with ion transport and nervous system processes, which can result in paralysis and death. It has been discovered that Cu NPs prevent different insect species from feeding and reproducing, which slows population growth and makes them useful pest management tools (Sharifi et al. 2022).

8.5.1 Application in integrated pest management (IPM)

Copper NPs are employed in integrated pest management (IPM), a multifaceted strategy of pest control that seeks to decrease the usage of chemical pesticides while promoting sustainability (Rodriguez et al. 2024). Because of their low environmental toxicity and broad-spectrum insecticidal efficacy, Cu NPs are frequently included in IPM techniques. Because they work well at low concentrations, less chemical is needed, which makes them a good substitute for conventional pest control methods (Athanassiou et al. 2018). Additionally, to increase overall efficacy, Cu NPs can be used with other pest control agents, such as chemical insecticides or biological controls like entomopathogenic fungi. In addition to raising pest mortality, these synergistic effects postpone the emergence of resistance in pest populations (Javaid et al. 2022).

For instance, research has shown that Cu NPs improve insecticidal efficacy by promoting oxidative stress and membrane disruption when combined with traditional pesticides such as pyrethroids or neonicotinoids. Cu NPs are useful components of IPM in crops including cotton, maize, and vegetables because they have successfully suppressed agricultural pests like *Helicoverpa armigera* (cotton bollworm), *Plutella xylostella* (diamondback moth), and *Spodoptera frugiperda* (fall armyworm) (Pavan et al. 2024). Their use in Nano formulations or as a foliar spray based on NPs guarantees long-lasting pest control effects, lowering the need for pesticide applications and encouraging more environmentally friendly farming methods (Yadav and Yadav 2018).

9. Case Studies: Efficacy of metallic NPs against specific insect pests

Several plant viruses like cotton aphid (*Aphis gossypii*) and green peach aphid (*Myzus persicae*) imbibe sap from plants and help in spreading plant viruses and ultimately harm crops significantly (Singh and Singh 2016). Among various MNPs, Ag NPs and ZnO NPs are two of them that have shown great efficacy against these aphids. Ag NPs break down the cuticle layer of aphids and induce oxidative stress which damages the overall cell structure and stops them from eating, in these ways they both disrupt their physiology and respiratory processes (Singh et al. 2018). Moreover, it has been researched that ZnO NPs damage the aphids by the production of reactive oxygen species (ROS) to check their population and prevent the spreading of plant viruses. According to studies, applying these NPs topically successfully lowers aphid infestations, offering a sustainable substitute for conventional pesticides (Mishra et al. 2022). Whiteflies, such as the sweet potato whitefly (*Bemisia tabaci*), are well known for damaging crops by spreading viruses and sucking sap. Whitefly populations have been successfully managed by metallic NPs like Cu NPs and Ag NPs (Milenovic et al. 2019). Ag NPs induce oxidative stress in whiteflies and by the production of reactive species these NPs damage and kill their cells, while Cu NPs affect the nervous system and metabolic processes of whiteflies to intensify the insecticidal action (Bihal et al. 2023). Because of their small size, these NPs can be administered as foliar sprays, which effectively suppress pests by penetrating the exoskeleton of whiteflies. Utilizing MNPs in integrated pest management (IPM) systems has been demonstrated to dramatically lower plant virus transmission and whitefly populations (Saurabh et al. 2021).

Cotton bollworm (*Helicoverpa armingera*) and yellow peach moth (*Conogethes punctiferalis*) harm the crops by boring them into fruits and vegetables. Various metallic NPs like Cu, ZnO, and Ag NPs showed better results against these pests (Ofuya et al. 2023). Reactive oxygen species (ROS) produced by Ag NPs and ZnO NPs cause chronic oxidative stress and damage cells in fruit borer larvae, decreasing their ability to eat and survive (Nawaz et al. 2023). Cu NPs cause pest mortality by further inhibiting metabolic activities. According to studies, using these NPs on fruit orchards can greatly lower borer infestations and enhance fruit quality, providing a long-term option for pest control (Bihal et al. 2023). Meloidogyne spp., or root-knot nematodes, are a significant agricultural pest that seriously harms plant root systems, resulting in decreased uptake of nutrients and water. Nematocidal activity has been shown by metallic NPs such as CuO, ZnO, and Ag NPs (Tapia-Vázquez et al. 2022). These NPs disrupt the nematode cuticle integrity and produce reactive oxygen species (ROS), which damage the nematodes oxidatively and ultimately result in their death (Khan et al. 2023b). Additionally, CuO NPs have a substantial inhibitory effect on the motility and hatching of worms. Metallic NPs are a crucial tool for managing root-knot nematodes in a sustainable and environmentally friendly way because studies have demonstrated that their application in soil can dramatically reduce nematode infestations while also increasing root health and crop yields (Khan et al. 2022).

10. Cost and scalability issues

Although MNPs, such as Cu NPs, ZnO NPs, and Ag NPs, have shown great promise in agricultural pest management, a number of scalability and cost issues prevent their widespread use. The high cost of producing NPs is one of the main obstacles (Raza et al. 2024). High-purity nanoparticle production is expensive due to the need for specific ingredients, complex machinery, and energy-intensive procedures (Kushnir and Sandén 2008). For example, because silver is a costly raw element, creating Ag NPs, which are renowned for their superior insecticidal qualities, can be costly. Because of this, small- and medium-sized farmers cannot afford to utilize nanoparticle-based pest control products widely, particularly in developing nations where cost is a major consideration when making agricultural decisions (Hassan et al. 2024). Scalability is still another important concern. Although small batches of NPs may be generated efficiently for laboratory and experimental uses, there are technical difficulties when scaling up production for large-scale agricultural use (Magalhães-Ghiotto et al. 2021). Mass production is made more difficult by the requirement for stability, uniform particle size, and the avoidance of aggregation during storage and use. Furthermore, the current level of nanoparticle technology frequently limits the creativity and financial resources needed to produce formulations that are simple to use in field settings, whether through sprays, soil treatments, or seed coatings (Wang et al. 2013). Scalability is also hampered by regulatory and environmental issues (Stensberg et al. 2011). Large-scale commercialization is further hampered by the absence of precise rules and regulatory frameworks for the use of NPs in agriculture, which increases uncertainty for producers and farmers (Zain et al. 2023).

13. Conclusion

Metallic nanoparticles such as silver, zinc and zinc oxide NPs, and copper showed efficient results in controlling both plant and animal insects, which offers an environmentally friendly alternative approach to various chemical pesticides and insecticides. These NPs are quite promising in their mode of action while combating hazardous insects through different mechanisms like the production of reactive oxygen species (ROS), induction of oxidative stress, physical damage to pest cuticle or cellular structure, and enzymatic disruption. For instance, Ag NPs effectively suppress aphids, ticks, mites, and whiteflies by penetrating exoskeletons and destabilizing physiological processes, while ZnO NPs reduce stored-grain pests like *Sitophilus oryzae* through ROS-mediated toxicity. Such innovations minimize environmental contamination, lower pesticide resistance risks, and enhance crop protection and livestock productivity. By addressing various barriers like cost-effective synthesis, field trials, and eco-friendly approaches MNPs could revolutionize pest control, aligning agricultural and livestock productivity with ecological sustainability to meet global food security demands amid climate change and population growth.

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