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NANOTECHNOLOGY IN PEST MANAGEMENT: A FOCUSED REVIEW ON THE ROLE OF SILVER NANOPARTICLES AGAINST COTTON PEST *PECTINOPHORA GOSSYPIELLA*

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ABSTRACT

Cotton (*Gossypium spp.)* is one of the major crops commercially grown for its natural fiber, which is affected by pink bollworm (*Pectinophora gossypiella*). *P. gossypiella* feeds on cotton seeds, lint, and fibers from inside the cotton bolls. Several toxic pesticides are being used to control its population, but it cannot be controlled once it enters the cotton bolls. Hence, nanotechnology is introduced for sustainable pest management, offering precision, efficacy, and environmental friendly as compared to conventional chemical methods, in which nanoparticles, especially silver nanoparticles (AgNPs), penetrate the exoskeleton of the insect body and affect its normal body function. Once AgNPs enter the insect body, they produce Ag^+ ions and reactive oxygen species (ROS), causing cellular toxicity, disruption in midgut epithelial cells, interference with enzyme activity and the respiratory system, disrupt ATP production, and induce oxidative stress. All these effects cause defects in the larval metabolism, feeding, and development, which cause mortality. Moreover, AgNPs can be prepared through the ecologically friendly green synthesis relying on plant extracts and reducing the environmental hazard caused by chemical synthesis. The application of AgNPs into cotton pest management systems is a potential approach that is environmentally friendly, resistance-free, and has the potential to offer profound protection of crops in the long run. This review identifies the mechanisms, synthesis strategies, and future opportunities of AgNPs in the effective management of *P. gossypiella* with the perspective of innovation in pest management practices.

Keywords: AgNPs, Cotton pest, Nanotechnology, *Pectinophora gossypiella,* Pest management.

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1. INTRODUCTION

Modern agriculture is facing multiple problems that reduce crop yield and production, which include climate change, price hikes, and resistance development in insect pests against insecticides and pesticides. Apart from this, biodiversity loss, reduction in the underground water level, increase in demand for food, and land degradation are also included in it (Khan & Idrees, 2024; Suchithkumar et al., 2024; Manzoor, 2025). Major crops like wheat, maize, rice, sugarcane, cotton, and legumes are contributing to fulfill a high portion of mankind's requirements (Kumar et al., 2023; Ramana et al., 2025). Cotton (*Gossypium hirsutum*) is a significant industrial and economic crop in the world, as it is a main source of natural fiber and a livelihood to millions of people (Gate et al., 2024; Yehia 2025). Cotton is a pillar of textile and economic growth, ranking 4th in yarn production, 2nd in yarn exports, and 7th in cloth production worldwide (Khan et al., 2024). Although the cotton crop poses a serious threat from multiple sucking and chewing pests, but it is most affected by whitefly (*Bemisia tabaci*) and pink bollworm (*Pectinophora gossypiella*) (Tauseef et al., 2025; Ullah et al., 2025).

Nevertheless, the *P. gossypiella* is causing most of the destruction, attacking flowers and bolls, feeding on seeds,

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and significantly lowering the lint production and quality of the fibres (Bitew & Abate, 2024; Narayan, 2024). To control them, traditional management processes, such as the massive use of insecticides and the use of Bt cotton, have become ineffective as insects have quickly developed resistance (Nagaraj et al., 2024; Selvarani et al., 2024). Even chemical pesticides, which are used to control pest attacks and their density, have hazardous effects on the natural environment (Borah & Biswas, 2023). To overcome this issue, nanoparticles (NPs) made up of noble metals like silver (Ag) and gold (Au) are being used in the field of integrated pest management (IPM). Due to their physicochemical properties and characteristics, NPs have become the center of interest in biomedical research (Meher et al., 2024). These NPs that are metallic in nature, have an immense importance in various fields because of their unique properties, are broadly applied to the domains of farming, textiles, and air cleaning (Shrivastava et al., 2023). Nanotechnology-based interventions, specifically, the use of silver nanoparticles (AgNPs), have recently portrayed a promising insecticidal potential against *P. gossypiella* management in cotton agroecosystems which includes the administration of oxidative stress, interference in gut physiology, and interference in metabolic pathways as a novel, sustainable, and target-specific solution (Kandil et al., 2024; Mallick & Rahman, 2025; Zohaib et al., 2026).

Nanotechnology is one of the emerging techniques that has tremendous potential in applied sciences such as biology, medicine, agriculture, pharmaceuticals, and genetic engineering (Khan et al., 2023). There are various categories of NPs based on their respective use, such as metal, metal oxide, polymer, carbon-based, and composites (Ghodrati et al., 2021). Their properties highly depend upon their size; the smaller the size, the more it determines the scope and use of nanomaterials (Jeevanandam et al., 2022). AgNPs are small particles and range between 1nm and 1000nm (Sadigh-Eteghad et al., 2022; Singhal 2024; Shahzadi 2025). AgNPs size is divided by the surface-volume ratio, implying that the smaller size of the NPs has a higher surface-to-volume ratio, as a consequence of a strong level of tunneling, the greater the reactivity of the particle, and the possibility to engage in biological processes (Dawadi et al., 2021; Jeevanandam et al., 2022). They possess certain electrical, magnetic, and light-specific features symbolized by various color and size changes (Dhanislas et al., 2023; Naderi-Samani et al., 2023). AgNPs have a high surface-volume ratio that increases the targeted pest control activity compared to bulk materials, such as fertilizers and pesticides. They are also used in the slow, focused, and specific regulation of pests as nanocarriers of conventional agrochemicals and active substances (Martínez-Cisterna et al., 2024; Alshamrani 2025). This is the characteristic of AgNPs that allows the researcher to employ numerous biological, physical, and chemical reactions in their production by accurately determining their size, shape, and density (Ahmad et al., 2022).

Researchers use a variety of approaches to the synthesis of AgNPs, such as green synthesis methods, green raw materials, and green synthesis, as well as environmentally friendly approaches (Bapat et al., 2022). They have put extracts of plant leaves and microbes to create successful nanopesticides against pests that cause disease, such as mosquitoes, ticks, and mites (Maťátková et al., 2022; Abbas et al., 2025). Silver that also possesses a biocidal (germ-killing) property is even more efficient when incorporated into an integrated approach to insect pest management in the form of AgNPs. The AgNPs are able to regulate pests using a number of physical and chemical mechanisms that allow them to penetrate through the hard exoskeleton of insects, disrupting their physical structure and physiological functions such as adenosine triphosphate (ATP) production and enzymes, which can eventually kill them (Jafir et al., 2023). In this review, we will discuss the importance of nanotechnology in agriculture as well as the use of AgNPs against a significant threat to the cotton crop, *P. gossypiella*. Several methods that are utilized in the synthesis of AgNPs, their properties, application strategies, methods for killing *P. gossypiella* by different physical and chemical processes, advantages, limitations and future prospects will also be discussed in this review article.

1.1. Silver Nanoparticles (AgNPs): Properties and Characterization

AgNPs possess specific physicochemical characteristics such as size, morphology and surface charge (Jeevanandam et al., 2022). They consist of atoms or molecules of a size of 1 billionth of a meter (10-9m) of various materials accumulated (Li et al., 2022). AgNPs also vary in forms or shapes like their size, which are spherical, rod-shaped, triangular, cubic, wire-like, and star-shaped (Zhang et al., 2022). The manipulation of the surface charge of AgNPs is necessary to attain accurate control over the behavior of the nanoparticles (Dubey et al., 2023). To change the surface charge, some strategies, including surface functionalization, could improve stability and reduce the toxicity and aggregation of particles (Akdaşçi et al., 2024). Besides, they are also highly conductive of electricity and heat because the outermost shell of silver contains valence electrons (Eker et al., 2025). AgNPs are excellent optical absorbers due to their surface plasmon resonance (SPR) and thus can be used as photocatalysts and sensors (Duman et al., 2024; Rupanshi et al., 2025). Some of the significant variables that can better the stability, solubility, and interaction of AgNPs are its surface chemistry, oxidation state, and ion release capacity (Sati et al., 2025).

AgNPs can be applied in biosensors, cryogenic superconductors, catalysts, microbial activity (Martínez-Cisterna et al., 2024), bioimaging, disease treatment, drug delivery, and nutraceuticals due to the properties of AgNPs. According to the description, the shape and structure of AgNPs are investigated with the use of transmission electron microscope (TEM) and scanning electron microscope (SEM) (Huda Abd Kadir et al., 2024).

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To determine the size distribution of AgNPs, a special equipment named Zetasizer Nano series analyzer is applied (Sati et al., 2025). Measures are made using an emission SEM coupled to the energy dispersive spectroscopy (EDS) apparatus based on the energy dispersive X-ray spectroscopy (EDS/ EDX) (Eker et al., 2025). Zeta-potential is used to measure the surface charge of AgNPs (Tiwari et al., 2025). Other devices employed in the additional characterization of AgNPs are multiple i.e. X-ray photoelectron spectroscopy (XPS), X-ray diffractometry (XRD), fourier transform infrared spectroscopy (FTIR), and ultraviolet-visible spectroscopy (UV-Vis) (Sagar et al., 2024). The synthesis of AgNPs is apparently confirmed by the determination of the plasmon resonance by UV-Vis spectroscopy (Nawabjohn et al., 2022). While XRD is employed to ascertain the crystallinity of a substance (Uzun 2023). The surface chemistry of AgNPs is investigated by FTIR (Pasieczna-Patkowska et al., 2025). For the precise measurement of electrical conductivity, volume resistance is evaluated by Loresta-GP MCP-T610 (Mitsubishi Chemical Corporation, Tokyo, Japan) resistivity meter (Eker et al., 2025). The properties and characteristics of AgNPs are discussed in Table 1.

1.2. Synthetic Approaches of AgNPs for Cotton Crop Protection System

The synthesis of AgNPs for the cotton crop protection system primarily focuses on getting controlled particle size, stability, and suitability for application in the field (Khan et al., 2023; Rabbi et al., 2024). It highly depends on the synthesis method, which is classified into two categories, i.e., top-down and bottom-up strategies, which are done by physical, chemical, and green synthesis methods (Nguyen et al., 2023). By using physical forces, including mechanical (crushing, grinding, and milling), thermal (vapor-condensation), and electrical forces (electrical arc discharge or laser ablation), NPs can be synthesized from bulk material in a top-down strategy (Bouafia et al., 2021). In this method, external forces are used in the form of light energy (laser ablation), electrical energy (electrical arc-discharge method), thermal energy (physical vapor deposition), and mechanical energy (ball milling method) because they do not utilize chemicals that can prevent NPs from clumping together, even if they have uniform size distributions and purities (Alharbi et al., 2022; Banerjee & Rai, 2022; Sharma & Bharti, 2023).

Meanwhile, the bottom-up approach concludes the synthesis of complex aggregates from molecular components through chemical and biological synthesis methods (Nguyen et al., 2023). Even though their toxic nature, the chemical synthesis of AgNPs provides high productivity yield, impressive quality, and controlled aggregation. In chemical synthesis, three reactive ingredients, such as a stabilizing compound, a reducing agent, and a silver salt, are combined (Lasmi et al., 2025). Since there are several chemicals that are hazardous to the natural environment utilized in the formation of NPs, their use is limited in the medical field. Therefore, biological synthesis is preferred to utilize that employ molecules from microorganisms, such as alcohols, flavonoids, alkaloids, quinines, terpenoids, and phenolic compounds, as well as exopolysaccharides, cellulose, and enzymes (Indiarto et al., 2022). This synthesis approach is cost-effective, favorable for the environment, easy to use, effective, and ensures better yield output (Zor et al., 2024). Researchers utilize natural extracts from plant leaves, bark, seeds, fruit extracts, and bacterial filters (Wang et al., 2024).

1.3. Mechanisms of Action of AgNPs against *P. gossypiella*

P. gossypiella feeds on the flowers, buds, bolls, and seeds of the cotton plant. The larvae of the first-generation feed upon the flower petals; they pull and twist the flower petals together and then feed from inside. These damaged flowers are called rosette flowers, where female *P. gossypiella* laid eggs, and their larvae of the second generation will bore into the cotton bolls, and then feed from the inside, damaging the seeds and fiber (Khan et al., 2024). Chemical pesticides were used to kill them, but it is quite difficult because they are present inside the cotton bolls (Khan et al., 2024). Furthermore, these pesticides are toxic in nature, and they are continuously corrupting our ecosystem. Therefore, researchers are focusing on using AgNPs synthesized by plant extracts against *P. gossypiella,* because it's difficult for them to develop resistance against AgNPs due to their unique properties (Zaidi et al., 2025). The feeding behavior of *P. gossypiella* on seeds, lint, and fiber from inside the cotton bolls is shown in Fig. 1.

AgNPs act through several toxic pathways to annihilate the *P. gossypiella*, which makes them effective against both exposed and concealed larvae (Gabarty et al., 2021; Pathipati & Kanuparthi, 2021; Kandil et al., 2024). The mechanism of action of AgNPs begins when larvae of *P. gossypiella* come into contact with AgNP-treated plant surface and tissue during feeding on cotton bolls (Pathipati & Kanuparthi, 2021). Due to electrostatic interaction, AgNPs cling to their cuticles and gradually penetrate or enter the body through spiracles and the digestive tract (Anees et al., 2022; Arjunan et al., 2024; Kandil et al., 2024). Once they enter the body, AgNPs release silver ions (Ag^+) that trigger the production of reactive oxygen species (ROS). These ROS molecules damage the vital cellular components, such as lipids, proteins, and DNA, and they also induce oxidative stress in the insect body (Martínez-Cisterna et al., 2024). The midgut epithelium, responsible for digestion and nutrient absorption, is one of the primary targets. AgNPs first disturb the epithelial lining, which causes the rupturing of the cell membrane,

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cytoplasmic leakage, and blocking enzyme activity that results in profound disability of nutrient assimilation, leading to starvation and developmental arrest (Gabarty et al., 2021; Kandil et al., 2024; Sharma et al., 2024).

Table 1: Properties and characteristics of AgNPs

Sr No.	Property	Interpretation	Range/ Values	Method of measurement	Importance	Influencing factors	Roles	References
1.	Size	Diameter of particle	1-1000nm	Zetasizer nano series analyzer	• Smaller size maintains a high surface-to-volume ratio • High reactivity • High penetration.	• Synthesis route • Capping agent	Critical for reactivity and bioactivity	(Dawadi et al., 2021; Restrepo and Villa 2021; Shahi et al., 2022; Sati et al., 2025)
2.	Shape	Morphology (spherical, rod-shaped, triangular, cubic, wire-like, and star-shaped)	Mostly circular or triangular	• TEM • SEM	• Different shapes show variation in respective activities • Cause a change in optical, catalytic, and electrical capabilities • Circular-shaped AgNPs are more reactive • Triangular-shaped AgNPs are more reactive in anti-bacterial action due to the presence of the basal plane	• Growth conditions • Surfactants	Affect Toxicity	(Zhang et al., 2022; Huda Abd Kadir et al., 2024; Eker et al., 2025; Sati et al., 2025)
3.	Surface charge	Electrical charge at the surface	±15–40mV	Zeta Analyzer	Major influence on stability and interaction with other molecules	• Electrolytes • Coating agents • pH	A higher charge makes the nanoparticle more stable	(Polinarski et al., 2021; Abd_Ellah et al., 2024; Girma et al., 2024; Eker et al., 2025; Godakhindi et al., 2025; Tiwari et al., 2025)
4.	Surface chemistry	Build-up of Coating and capping molecules	• Citrate • PVP • Plant extracts	FTIR	Great impact on stability and biocompatibility by acting as reducing or stabilizing agents.	• Green synthesis • Chemical synthesis	Toxicity decreases with the use of green capping	(Ali et al., 2023; Menichetti et al., 2023; Pasieczna-Patkowska et al., 2025)
5.	Crystal structure	Arrangement of atoms or molecules	Face-Centered cubic (Fcc) Ag nanocrystals	XRD	Substantial consequences of optical, catalytic behavior	• Temperature • Synthesis rate	To check crystallinity	(Uzun, 2023; Dwivedi et al., 2024)
6.	Optical property	Surface plasmon resonance	1-100nm	UV-Vis	Helps in formation and photothermal uses	• Size • Shape	Corresponds to aggregation	(Nawabjohn et al., 2022; Beck et al., 2023; Akdaşçi et al., 2024)
7.	Aggregation state	Cluster of particles	Monodisperse	TEM	Affects mobility and efficiency	Surface charge pH	Reduction in reactivity	(Dubey et al., 2023; Akdaşçi et al., 2024)
8.	Ion release	Dissolution of silver ions	Coating dependent	XPS Electrodes	Helps in antimicrobial effects	• Oxygen • pH	Directly related to toxicity	(Xu et al., 2021; Kyziol-Komosinska et al., 2024)
9.	Surface area	Area per unit	1-100nm	BET analysis	Helps in high reactivity	Size of particle	Important for catalytic action	(Husain et al., 2023; Junejo et al., 2024)
10.	conductivity	Electrical / Thermal	Higher vs bulk for electrical; Thermal 429W/mK at room temperature	Resistivity meter	High impact on sensors and coating	Capping	Relevant in pest control	(Eker et al., 2025)

Moreover, AgNPs disturb the respiration and ATP production by disrupting the metabolic pathways through binding to the thiol group (-SH) in proteins and enzymes (Abdou & Zyaan 2023; Jafir et al., 2023; Kandil et al., 2024). AgNPs amend the nerve signal transmission, causing paralysis and feeding cessation through neurological disruption (Suthar et al., 2023). They weaken the immune system of the larvae, making them more susceptible to other diseases or infections (Gabarty et al., 2021; Khan et al., 2024). Due to all of these mechanisms, oxidative stress, gut tissue destruction, enzyme inhibition, and immune suppression ultimately result in weakening of larvae. This leads *P.gossypiella* to a reduction in mobility, cessation of feeding, pupation failure, and an increase in mortality (Gabarty et al., 2021; Kandil et al., 2024). The multifaceted toxicity of AgNPs also minimizes the risk of resistance development, making them a promising nano-insecticidal tool for cotton pest management (Luneja & Mkindi, 2025). The process of AgNPs killing *P. gossypiella* is shown in Fig. 2.

1.4. Application Strategies of AgNPs

AgNPs are applied in the field in various ways that include foliar spray of AgNPs, seed treatment with AgNPs, nanocoating with cotton bolls, soil application of AgNPs, integrating with pheromone traps or biological control agents, and post-harvest treatment with AgNPs (Kale et al., 2021; Khan et al., 2023; Khan et al., 2024;

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Tokarz et al., 2024; Kumar et al., 2025; Ullah et al., 2025; Zaidi et al., 2025). Hence, there are several application strategies of AgNPs used against *P. gossypiella* in the field or in the laboratory, which are discussed in a comprehensive Table 2.

Table 2: Application strategies of AgNPs used against *P. gossypiella*

Sr No.	Application strategy	Target pest stage	Mode of action	Advantages	Limitations	Future research scope	References
1.	Foliar spray of AgNPs	• Eggs • Early instar larvae on leaves, squares, flowers	• Direct contact • Ingestion • Disruption of the gut • turmoil of the cuticle	• Fast knockdown • Easy to apply in the field • Covers up large area.	• Ineffective against larvae because they are already inside the cotton bolls, it may need numerous sprays	• Development of a formulation with improved leaf adhesion	(Dikshit et al., 2021; Ahmed et al., 2022; Mallick & Rahman 2025)
2.	Seed treatment with AgNPs	• Early larvae in the germination stage	• Systematic uptake in seedlings through the process of ingestion	• Show long-lasting protection at the seedling stage • Reduce the pest infestation at the initial stage	• An optimized dose is required to avoid phytotoxicity	• Efficient and improved systemic translocation in plants.	(Ikram et al., 2025; Mallick & Rahman 2025; Mylsamy et al., 2025; Ningthoujam 2025)
3.	Soil application of AgNPs	• Pupae • Hibernating larvae in soil debris	• Toxicity through soil contact disrupts the process of pupation	• Stop the life cycle of pests in the soil • Stop pest in the pupation process • Control overpopulation	• High leaching risk • harmful to soil microbes	• Develop nanogranules safe for soil ecology while being released slowly	(Gabarty et al., 2021; Khan et al., 2023; Martínez-Cisterna et al., 2024; Ningthoujam 2025)
4.	Nanocoating on cotton bolls	• Larvae entering through the boll rind after boring	• Physical barrier (stomatal blockage, encapsulation of the target) • Nanoparticle toxicity (size, concentration)	• Protect fruiting bodies (cotton bolls) directly • Inhibit the entry of larvae	• Application in the field is quite difficult • Takes a long time to apply nanocoating on cotton bolls • High manual handling is required	• Cost-effective nanobarrier films are under development	(Abou Elmaaty et al., 2022; Anees et al., 2022; Kandil et al., 2024)
5.	Integration with pheromone traps (nanobaited traps)	• Adult moths (before egg laying)	• Attraction (fascinate and lure the male adult moths that are ready to breed) • Contact toxicity	• Eco-friendly • Reduce the population of adult moths • Disrupt their breeding process • Control the emergence of the next generation	• Helpful to control only adults • a high density of traps is required	• Smart nanocarriers will be developed for sustained pheromone release	(Rizvi et al., 2021; Ali et al., 2023; JAMS 2023)
6.	Combination with biological control agents	• Larvae • Pupae • Eggs	• Synergistic toxicity (an interaction when the combined toxic effect of two or more substances is greater than the sum of the individual toxicities) • Biological attack	• Delays resistance development in pests • Shows broad-spectrum control	• Risk of harming beneficial insects	• Research on selective nanoformulation that will be safe for beneficial insects	(Gabarty et al., 2021; Li et al., 2025; Zaidi et al., 2025)
7.	Encapsulation with nanocarriers	• Larvae feeding inside the bolls	• Controlled and slow release of AgNPs inside plant tissues	• Longer persistence • Higher penetration • Reduced application frequency	• High production cost • yet not ready for use in the field.	• Precise and targeted delivery	(Ibrahim et al., 2022; Salman et al., 2023).
8.	Post-harvest treatment	• Surviving larvae • Surviving pupae • Diapause larvae in unopened cotton bolls	• Residual nanoparticle toxicity prevents carryover	• Reduced infestation in the next crop cycle • Prevents stored cotton	• Safe dosage for humans and livestock must be ensured	• Develop residue-free nano-treatments for seed industry	(Chanu & Singh. 2022; Jasrotia et al., 2022; Negi & Moses 2025)

1.5. Challenges and Future Prospects

AgNPs are being used in several domains due to their unique properties, but they have potentially hazardous effects on crop plants that limit their use (Huang et al., 2022; Kumar et al., 2023). The phytotoxicity concerns, environmental persistence, non-target effects, resistance or adaptation risk, high production cost, high stabilization cost, and limited field data are included in it (Tripathi et al., 2023; Guru et al., 2025). The high concentration of AgNPs causes oxidative stress and growth inhibition in the cotton plant, resulting in damaging plant physiology (Khan et al., 2021; Siddiqi and Husen 2022). Recent research emphasizes the need for caution in the prolonged use of AgNPs, especially metallic ones, because they can be hazardous to the natural environment (Gao et al., 2023).

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They may also have harmful effects on beneficial insects, such as predators, parasitoids, or pollinators (Martínez-Cisterna et al., 2024). Moreover, the advancement of nanotechnology in several fields indicates the need for safe methods for the synthesis of nanoparticles that are more effective, efficient, less harmful, and more favorable for the environment (Guru et al., 2025).

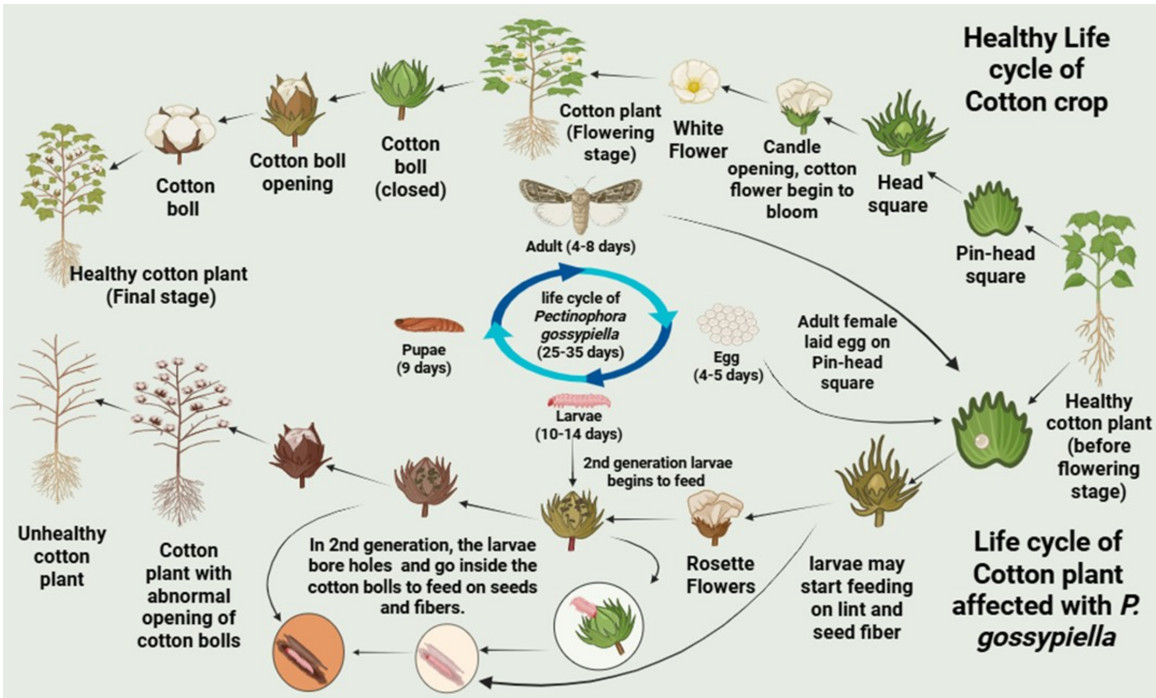

Fig. 1: Life cycle of cotton plant with the infestation of *P. gossypiella*.

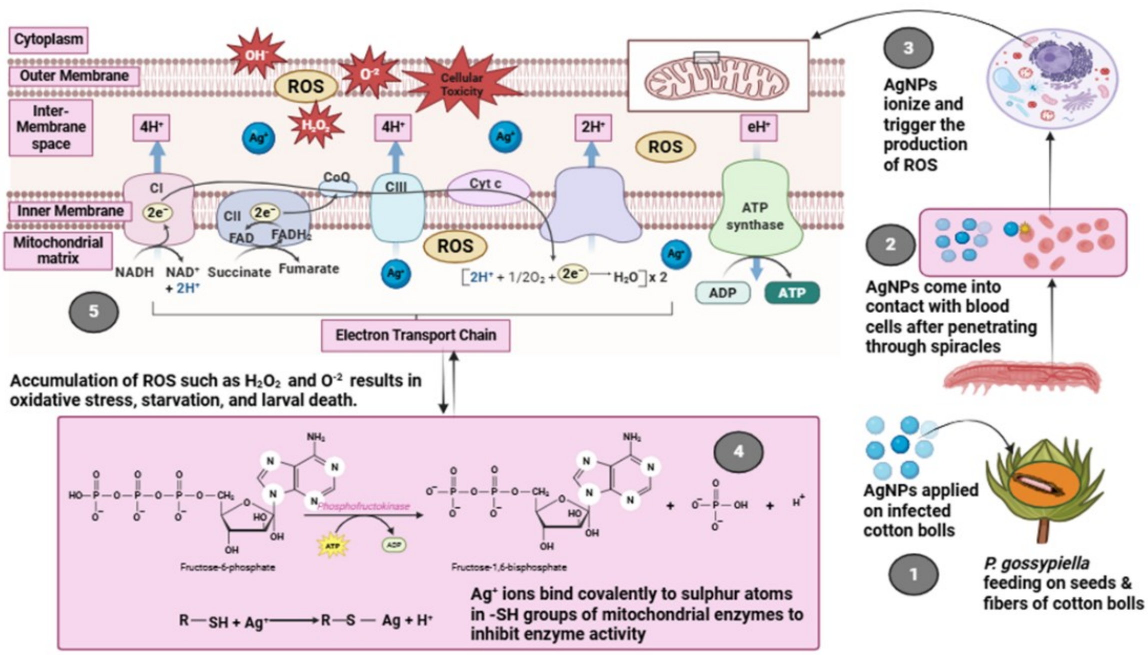

Fig. 2: Mechanism of AgNPs to kill *P. gossypiella* through different metabolic pathways.

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Future research focuses on the efficient synthesis (green, physical, or chemical) approaches of AgNPs, improvement in nano-formulation, and a precise delivery system. The integration of AgNPs with biological control agents, pheromone traps, and IPM programs is also the center of interest for researchers to enhance the efficacy of the use of AgNPs. Researchers are also conducting research on the toxicological or risk assessment of AgNPs to decide their fate in soil, plants, and the ecosystem. However, the potential benefits of AgNPs in pest management are still uncovered due to a lack of research on AgNPs in the field, under the conditions of a natural ecosystem. There is still a vast requirement for the application of AgNPs in the field of major crops because most researches are done only in the controlled environment of labs.

2. CONCLUSION

In conclusion, the major cotton crop has a serious pest, *P. gossypiella.* Due to its unique attacking pattern, feeding inside the cotton bolls, it is difficult to control it with insecticides. To overcome this issue, AgNPs are used to annihilate the *P. gossypiella* through various application strategies such as foliar spray of AgNPs, soil application of AgNPs, seed treatment, and nanocoating of cotton bolls with AgNPs, integration of AgNPs with pheromone traps or biological control agents, and post-harvest treatment of AgNPs. Due to its tiny size, AgNPs can easily penetrate the insect body through the cuticle, oral cavity, and spiracles. It disintegrated the normal body functions of an insect, such as weakening the immune system, disruption in enzyme activity, and ATP production. Regardless of these benefits, AgNPs also have some limitations, such as phytotoxicity concerns, high production costs, and potential other hazards. In the future, this technology will rule pest management through improvements in synthesis, formulations, and delivery systems.

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Generative AI Statements: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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