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Green synthesis of silver nanoparticles for the biocontrol of insect pests

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Abstract
The development of eco-friendly and sustainable approaches for pest management is a key priority in agricultural and environmental sectors. In this study, we explore the green synthesis of silver nanoparticles (AgNPs) as an effective biocontrol agent against insect pests. Utilizing plant extracts as reducing and capping agents, we demonstrate an environmentally benign method for the synthesis of AgNPs, which eliminates the need for toxic chemicals. The insecticidal activity of the AgNPs was evaluated against common agricultural pests, demonstrating significant mortality rates and disruption of pest life cycles. Traditional chemical synthesis methods for nanoparticles are often expensive, toxic, and environmentally hazardous. In contrast, green synthesis utilizes natural sources such as plants, microbes, and biopolymers, offering a sustainable alternative with minimal ecological impact. Green-synthesized AgNPs hold promise as a sustainable alternative for pest control, offering a reduction in the use of synthetic pesticides and contributing to the overall health of agroecosystems. The biocompatibility, cost-effectiveness, and ease of large-scale production further highlight the potential of this approach for integrated pest management strategies.

Keywords: Green synthesis, silver nanoparticles, insect biocontrol, plant extracts, sustainable pest management

Introduction

Green synthesis refers to the creation of nanoparticles via biological, environmentally safe methods, leveraging natural compounds from plants or microorganisms as reducing agents. This sustainable synthesis process aligns with the principles of green chemistry, which emphasizes reduced toxicity and waste, biocompatibility, and cost-efficiency. The importance of biocontrol in agriculture cannot be overstated, as it aims to target specific pests with minimal impact on the surrounding ecosystem. Traditional biocontrol strategies, though effective, sometimes fall short due to the limited availability of biological agents and varying levels of effectiveness. Green-synthesized silver nanoparticles, with their biocidal properties, offer a bridge between traditional biocontrol and modern nanotechnology, potentially providing enhanced pest control with reduced environmental footprint. (Salomi *et al*., 2023) [1]. The average lifespan of an adult male is ten days, whereas the average lifespan of an adult female is between forty-two and fifty-six days. There are ectoparasites that live on people and animals kept as pets. They are designed to facilitate the transmission of infectious agents that cause illnesses in humans include Mexico, Central America, Africa, and Asia. There is a wide variety of mosquito species that may be found in the various regions of the world. In general, they are responsible for the transmission of human illnesses such as Malaria, Dengue, Filariasis, Yellow Fever, and Chikungunya, which ultimately leads to the deaths of millions of people.

The Anopheline species are the primary vectors of transmission of malaria in India. It was estimated that between two and three million people were affected by malaria for each year. Other genera, like as Aedes aegypti, are responsible for the transmission of dengue fever, which is caused by arbovirus and is generally found in tropical and subtropical regions. A total of 209 villages in the state of Maharashtra were affected by dengue disease. (Saranraj *et al*., 2022) [2]. Since 2005, around 80,000 persons in the states of Karnataka and Andhra Pradesh have been afflicted with the virus. Filariasis is caused by the *Culex quinquefasciatus* mosquito, which is a vector for Wuchereria species.

It is generally agreed that nanotechnology is the sixth revolutionary technology that has emerged over the past hundred years. Since the beginning of twenty-first century, the knowledge that has been acquired in these fields has been transferred and modified in the agricultural sector in order to make use of it for the creation of agrochemicals that protect plants. The term "Nanotechnology" refers to the process of controlling objects at dimensions ranging from one to one hundred nanometres (nm), where distinctive phenomena and fresh applications are involved. Materials at the nanoscale have qualities that are radically different from those of bulk materials and individual molecules. These features include physical, chemical, and biological aspects. (Su *et al.*,1998) [4].

Mechanism of Green Synthesis of Silver Nanoparticles

The green synthesis of AgNPs utilizes natural extracts from plants, bacteria, fungi, or algae to reduce silver ions into nanoparticulate form. Plant-based synthesis is particularly popular due to the availability, diversity, and bioactive compounds found in medicinal plants such as neem, tulsi, and eucalyptus. In the synthesis process, plant extracts containing bioactive phytochemicals (like flavonoids, terpenoids, and phenolic acids) are combined with silver nitrate ($AgNO_3$), which serves as a precursor. These phytochemicals act as reducing and stabilizing agents, leading to the formation of stable silver nanoparticles without the need for toxic chemicals typically used in conventional synthesis. This process not only minimizes environmental impact but also enhances the bioactivity of the nanoparticles, often due to the presence of additional plant compounds on their surface (Saranraj *et al.,* 2010) [5].

Green Synthesized Nanoparticles Against Mosquito Vector

Green-synthesized nanoparticles (NPs) represent a promising, eco-friendly approach for controlling mosquito vectors responsible for spreading serious diseases like Malaria, Dengue, and Zika. Using plant extracts or Microbial agents, Nanoparticles such as silver (AgNPs), gold (AuNPs), zinc oxide (ZnO NPs), and copper oxide (CuO NPs) can be synthesized in a sustainable manner, avoiding the harmful chemicals typically used in traditional mosquito control. These green-synthesized nanoparticles exhibit larvicidal, adulticidal, and sometimes repellent properties, effectively disrupting mosquito cell membranes, inducing oxidative stress, and inhibiting enzymatic functions, ultimately leading to mosquito mortality (Siva Sakthi *et al.,* 2011) [6]. Studies have shown that nanoparticles synthesized from plants like neem, tulsi, and eucalyptus exhibit strong activity against mosquito species such as *Aedes aegypti*, *Anopheles gambiae*, and *Culex quinquefasciatus,* impacting both larval and adult stages. Characterization of these nanoparticles (e.g., using UV-Vis spectroscopy, SEM, and TEM) is essential to understand their size, shape, and stability, as these factors influence their efficacy. Additionally, green-synthesized NPs offer advantages over conventional insecticides, such as reduced environmental impact and lowered risk of resistance in mosquitoes. However, ensuring the safety of non-target organisms and assessing environmental impact remain critical for large-scale applications of these nanoparticles in vector control programs. (Murugan *et al.,*2011) [7].

Nanoparticles such as silver (AgNPs), gold (AuNPs), zinc oxide (ZnO NPs), and copper oxide (CuO NPs) have shown potent larvicidal and adulticidal properties against mosquitoes. The mode of action involves multiple mechanisms: green-synthesized nanoparticles can disrupt mosquito cell membranes, induce oxidative stress, interfere with respiratory enzymes, and inhibit metabolic processes essential for growth and reproduction. This multi-faceted approach not only causes mortality in larvae and adult mosquitoes but also serves as an effective repellent and oviposition deterrent, thus reducing mosquito breeding potential (WHO, 1996) [8].

The synthesis of these nanoparticles is relatively straightforward, requiring only the combination of plant extracts with metal precursors (e.g., silver nitrate for AgNPs), where bioactive compounds in the plant act as reducing and stabilizing agents. Characterization techniques like UV-Vis spectroscopy, scanning electron microscopy (SEM), transmission electron microscopy (TEM), Fourier-transform infrared spectroscopy (FTIR), and X-ray diffraction (XRD) are employed to analyze nanoparticle size, shape, stability, and the functional groups involved in synthesis. These characteristics play a significant role in determining the efficacy of nanoparticles for mosquito control, as smaller, stable particles have been found to penetrate cells more effectively. (Saranraj *et al.,* 2024) [9].

Table 1: Green-synthesized AgNPs for insect biocontrol, from synthesis methods to applications and advantages

Category	Details
Purpose of Control	Sustainable, eco-friendly insect biocontrol; reduces dependency on conventional pesticides
Type of Nanoparticles	Silver Nanoparticles (AgNPs)
Synthesis Method	Phytochemicals in plant extracts (flavonoids, phenols, terpenoids), microbial metabolites
Mechanisms of Insecticidal Action	➢ Disruption of cell membranes ➢ Generation of reactive oxygen species (ROS) causing oxidative stress ➢ Interference with enzyme activity and cellular functions ➢ Silver ion release causing cytotoxicity and mortality
Target Insect Stages	Effective primarily against larvae and adults of insect pests
Advantages of AgNPs	➢ High insecticidal efficiency at low doses ➢ Slow-release effect with prolonged efficacy ➢ Reduced environmental impact compared to chemical insecticides ➢ Low risk of resistance development due to complex mechanisms
Application Methods	➢ Larvicidal treatments in water sources ➢ Sprays ➢ Coating on bed nets or traps
Environmental Impact	Generally lower toxicity to non-target organisms with green synthesis; requires further ecological impact studies

Biocidal Mechanisms of Silver Nanoparticles Against Insects

The insecticidal properties of AgNPs can be attributed to several mechanisms. Primarily, silver nanoparticles interact with the insect's cellular structure, disrupting cell membranes and inducing oxidative stress. This oxidative stress generates reactive oxygen species (ROS) within the cells, leading to the breakdown of critical cellular components like DNA, proteins, and lipids. The nanoparticles can also interfere with enzyme activity, thereby disrupting essential metabolic functions and resulting in insect mortality. Another mechanism involves the gradual release of silver ions, which have been shown to bind to cellular thiol groups, affecting protein functions and causing cytotoxicity. These multi-target mechanisms make it challenging for insects to develop resistance, offering a potential advantage over conventional insecticides, which often target a single physiological pathway.

Fig 1: *Coleoptera*

Fig 2: *Caelifera*

Nanotechnology for Insect Pest Control

According to the findings of recent research, platforms made of engineered nanomaterials (ENM) have the potential to offer effective techniques for the management and control of weed species and parasitic insects. Through the use of nano-emulsification and nanoencapsulation, nanogenic formulations that include ENM into conventional insecticides and herbicides have the capability to enhance the penetrability, solubility, stability, and controlled release qualities of the active ingredient in the target species. In order to limit the amount of material that is released into the system, it is possible to increase the precision and accuracy of the distribution of active components, such as nano fertilisers and antimicrobials. Nanoparticles are controlled by the atomic structure, which also influences their size, shape, and orientation in relation to reactions about the issues that are being addressed. The remarkable strength, great chemical reactivity, and high conductivity of nanoparticles are some of the new characteristics that they possess. Nanopesticides can be found in a variety of forms, such as micelles and particles, and they can be composed of organic (such as polymers) and/or inorganic (such as oxides of metals) components to achieve their desired effects.

Traditional techniques of insect pest management can be improved in terms of precision, efficiency, and environmental safety through the application of nanotechnology, which provides creative solutions for the problem. In order to limit the quantity of chemicals that are required, nanotechnology makes use of nanoparticles to distribute pesticides in a controlled and targeted manner. This helps to minimise the amount of damage that is caused to ecosystems and species that are useful to the environment. The use of nano-encapsulation makes it possible for pesticides to be released gradually, which increases their efficiency and decreases the frequency with which they must be applied. Furthermore, nanoparticles have the ability to enhance the adherence of pesticides to the surfaces of plants or the cuticles of insects, so making treatments more effective against pests that are resistant to the pesticides. Additionally, nanotechnology makes it easier to employ biological agents, such as chemicals derived from plants or microorganisms, hence improving the stability and delivery of these agents for the purpose of pest management. This strategy not only helps battle insect species that are resistant to pesticides, but it also helps prevent environmental pollution, making it a more sustainable and effective solution for managing pest populations.

Emerging field of Nano-Pesticides for controlling insect pests

Nano-formulations of several sorts are typically employed for the purpose of controlling insect pests. The term "nano-formulation" refers to any formulation that has materials that are nanometre in size and has either organic polymers or inorganic metal oxides as its constituents. To enhance the solubility of poorly soluble active ingredients (a.i.) or to release the a.i. in a gradual and targeted way and/or to preserve the a.i. from premature degradation are the primary goals of nano-pesticide formulations. It is also possible to achieve both of these goals simultaneously. (Dineshkumar *et al.*,2017) [11]. For the purpose of producing pesticide nanoformulations, a wide range of natural and synthetic particles, including metal, metal oxides, non-metal oxides, carbon, silicates, ceramics, clays, layered double hydroxides, polymers, lipids, dendrimers, proteins, quantum dots, and so on, are utilised. When it comes to nanostructured systems, polymeric nanoparticles are utilised for the creation of controlled release products. (Broadbent. 1984) [12]. Recent years have seen its application in the delivery of pesticides, in which the active chemicals are loaded with polymer that falls within the nanoscale range of one to one thousand nanometres.

Nano-emulsions, nano-particles, and nano-capsules are the several types of nano-based insecticides that are most often utilised. In addition to this, nanogel, nanospheres, and nanosuspension are other common nano-systems in the field of insect pest management today.

Insect pests are being controlled in a manner that is being revolutionised by the developing field of nano-pesticides. This is being accomplished through the use of nanotechnology to improve the effectiveness, accuracy, and sustainability of pest management. Nanopesticides are created with nanoscale particles or structures that increase the delivery, targeting, and controlled release of active components. In a reduction in the quantity of chemical pesticides that are required, which in turn minimises the impact that these pesticides have on the environment. It is possible to these nanoparticles such that they cling more effectively to plant surfaces, that they are resistant to degradation, and that they are more quickly ingested by insects. (Golulakrishnan *et at.*,2012) [13]. This would ensure that pests are specifically targeted while beneficial creatures and the ecosystems that surround them are completely unaffected. In addition, nano-encapsulation of pesticides enables a delayed and sustained release, which extends the duration of the treatment's effectiveness and reduces the number of times it needs to be applied.

Entomological nanotechnology applications

New agrochemicals and distribution methods are made available by nanotechnology, which also promises to reduce the amount of chemical dosages utilised in order to boost crop output. It is possible to efficiently boost crop yield using the agrochemicals that are accessible, as well as reduce diseases and pests. On the other hand, it calls for a significant amount of affectivity and application without discrimination. Through the use of encapsulation and coating, the nanotechnology application intends to decrease the amount of agrochemicals that are administered. The study of insects is combined with modern nanotechnology in the discipline of entomological nanotechnology, In the development of creative applications across a variety of fields. (Baranitharan *et al.*, 2014) [14]. One of the most important areas is agriculture, where nanodevices inspired by insects are being developed to improve pest management by using nanocapsules containing pesticides that have a controlled release, so reducing the amount of damage done to the environment. For the purpose of targeted medication administration, insect-inspired systems are now being investigated in the field of medicine. These systems aim to imitate the accuracy of the mosquito proboscis in delivering chemicals directly to specific cells. Additionally, bio-hybrid nanorobots that are modelled after the flight and movement of insects are gaining popularity in environmental monitoring and search-and-rescue operations. (Schmutterer, 1990) [15]. These nanorobots offer microdrones that are both efficient and nimble, and they are capable of negotiating hard settings. Nanosensors that are extremely sensitive are being inspired by the natural ability of insects to sense chemical changes in their environment. These nanosensors may detect pollutants or poisons. Through the use of the one-of-a-kind biological characteristics of insects, entomological nanotechnology has the potential to bring about significant advancements in the fields of sustainability, healthcare, and robotics.

Entomological nanotechnology is a combination of the biological advancements made by insects with the most cutting-edge nanotechnology. This combination enables a broad variety of applications in disciplines such as agriculture, health, environmental research, and robotics. It is possible to generate controlled-release pesticides in agriculture by using nanoformulations that are inspired by the behaviour of insects. These pesticides have a little impact on the environment while simultaneously improving efficiency and targeting pests more efficiently. In addition, nanomaterials that are modelled after the exoskeletons of insects offer durability and strength, which has led to the creation of improved biomaterials that may be utilised in the field of tissue engineering and medical devices. (Ruskin, 1992) [16]. Nanoscale drug delivery systems have been inspired by the accuracy of insect processes, such as the proboscis of the mosquito, in the area of medicine.

These systems are able to provide pharmaceuticals precisely to specified cells, which improves the effectiveness of therapy while simultaneously lowering the impact of any adverse effects. The capacity of insects to sense and react to minute changes in their surroundings has led to the development of very sensitive nanosensors that are capable of detecting pollutants and poisons in the environment. These nanosensors have been used in environmental monitoring. (Kalyanasundaram *et al.*,1985) [17]. When it comes to robotics, bio-hybrid nanorobots, which are modelled after the movement and flying capabilities of insects such as bees and dragonflies, provide new possibilities for microdrones that are employed in search and rescue missions, surveillance, and environmental monitoring. Their diminutive size and high energy efficiency, these nanobots are able to negotiate complicated settings with ease, making them an excellent choice for usage in locations that are difficult to access. In addition, nanostructures that are inspired by insects are being used to generate super hydrophobic surfaces for water-resistant materials. Additionally, anti-reflective coatings that are based on insect eyes are being used to improve optical equipment. (Abbott, 1952) [18]. In general, entomological nanotechnology is a remarkable combination of technical innovation and biological development. It offers novel approaches to addressing some of the most important problems in the fields of advanced engineering, healthcare, and sustainability.

Conclusion

The green synthesis of silver nanoparticles offers an innovative, sustainable approach to insect biocontrol, aligning with the principles of environmental safety and effectiveness in pest management. By leveraging biological resources, green-synthesized AgNPs achieve significant insecticidal activity with minimal impact on non-target species. While there are challenges in scalability, regulation, and consistency, ongoing research is poised to address these limitations. As interest in eco-friendly agricultural practices grows, green-synthesized AgNPs are likely to play an increasingly important role in integrated pest management, reducing the environmental impact of pest control and paving the way for more resilient, sustainable agricultural systems.

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