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Nano-Biotechnology and Insect Pest Management: A Future Paradigm

*Smruti Shikha Parida[1] and Manish Ray[2]
[1]M.Sc. Scholar, Department of Agricultural Biotechnology, College of Agriculture, OUAT, Bhubaneswar-751003
[2]M.Sc. Scholar, Department of Entomology, College of Agriculture, OUAT, Bhubaneswar-751003
*Corresponding Author's email: smrutiskparida@gmail.com

Biotechnology: Where biology with technology meets the future—harnessing nature's own technology to heal, protect, fuel and feed the planet." The field has evolved from lab-based discovery to real-world execution, merging with biological systems to create a more sustainable, healthy, and high-tech future. The integration of biotechnology into insect control marks a reformative shift toward highly precise, environmentally conscious pest management method.

Introduction

Late in the 20th century, nano-biotechnology and bio-nanotechnology are completely new notions, and biotechnology has been only over several generations, their ambit is still being specified. This technology enables the development of highly specific and targeted pest control agents that can be delivered in smaller, more effective doses, thereby reducing the overall chemical load in the environment.

Aim and Objectives

Nano-biotechnology in insect pest management intends to replace the conventional chemical methods with precise, sustainable, and highly efficient alternatives. Its primary objectives focuses on maximizing the pest mortality while diminishing the collateral environmental and health impacts. Sustainable Agriculture, target delivery accuracy, controlled release and early detection and monitoring etc. are the key aim for promoting and adapting this technique.

Types of Approaches

Nano-biotechnology integrates sensors and smart delivery systems to detect and eliminate pests with molecular precision. This approach physically disrupts pest functions while minimizing chemical use, ensuring highly targeted and efficient crop protection. These methods range from advanced delivery vehicles to molecular-level gene silencing. Some of the approaches are:

- **Nano-Encapsulation:** Active ingredients are enclosed in protective shells like chitosan, calcium alginate, or synthetic polymers. This allows for a controlled, slow release of the pesticide over time, reducing the need for frequent re-application.
- **Enzyme-Triggered Release**: Formulations can be designed to activate only upon contact with specific enzymes, such as laccase, ensuring higher specificity to target pests.
- **Nano-Mediated RNA Interference (RNAi):** Nanoparticles (such as carbon dots or liposomes) are used as vehicles to deliver double-stranded RNA (dsRNA) into the

insect. This silences vital genes, effectively killing the pest or preventing its reproduction without affecting non-target species.

- **DNA-Tagged Nanoparticles:** Metallic nanoparticles can be tagged with specific DNA sequences to target the genomic level of pests like the fall armyworm.
- **Nanosensors:** It represents a significant advancement in the early detection of pest infestations. These sensors operate based on the detection of specific biochemical markers or volatile organic compounds (VOCs) emitted by pests, which allows for rapid identification of infestations before they become widespread.
- **Biochemical Markers**: Gold nanoparticles functionalized with antibodies can identify specific proteins related to pest activity, providing real-time data for integrated pest management (IPM).
- **Oxidative Stress:** Metallic nanoparticles (silver, gold, zinc, copper) penetrate the insect's body and generate reactive oxygen species (ROS), which damage cellular DNA and proteins.
- **Nano-gel:** This nano-gel is chemically, thermally and mechanically more stable than natural pheromone and it lowers down the evaporation of the highly volatile pheromone methyl eugenol (ME) and protects it from the degrading by environmental factors like exposure to air, water and sunlight.
- **Botanical nano-pesticide:** Botanicals offer an environmentally benign solution for the management of insect pests; however, their application is limited due to their low stability in environment. Nanostructured botanicals such as Azadirachtin, rotenone, carvacrol, thymol, curcumin etc are very effective against insect pest. etc.

Advantages of the approaches

- Precision, high surface-area-to-volume ratio and Targeted delivery system ensuring that pesticides are delivered exactly where and when they are needed.
- Nano-encapsulation protects sensitive biopesticides (like neem oil or Bt toxins) from rapid degradation by UV light, rain, and temperature, extending their field life and reducing the frequency of application.
- Enhanced Bioavailability making them easier for insects to absorb and harder for them to develop resistance against.

Disadvantages of the approaches

- Unknown Eco-toxicity and bioaccumulation can potentially disrupting local ecosystems and poses long-term risks to human and animal health.
- Cellular and Genetic Stress can cause unintended oxidative stress or DNA damage in crops, leading to reduced seed germination or inhibited root growth at high concentrations.
- High Production Costs of production and expertise for the synthesis of technique compared to traditional pesticides.
- Regulatory Gaps in agricultural markets for harmonized safety guidelines and standardized testing protocols, hindering their widespread legal adoption.

Physiological Impacts and Ecological Concerns

Despite balance in usage, nano-biotechnology presents notable safety concerns. Because nanoparticles can penetrate cell membranes and organelles, they may induce cellular toxicity, leading to oxidative stress, mitochondrial dysfunction, and DNA damage. Additionally the Studies have shown that certain nanomaterial can affect soil health by impacting the growth and activity of beneficial microbes, which are essential for nutrient cycling and plant growth. Similarly, nanoparticles entering aquatic systems can have toxic effects on aquatic organisms, including fish and invertebrates, potentially disrupting food webs and ecosystem balance. To address these concerns, ongoing research is needed to understand the fate and transport of nanomaterial in various environmental compartments and to develop strategies for mitigating their potential risks.

Future Outlook

The future of nano-biotechnology in insect pest control is centred on creating a "zero-residue" agricultural ecosystem. Outlook of farming is moving toward "smart" protection by ditching the toxic chemical blankets for the biodegradable as well as molecular nano-carriers to seek out specific pests and release their payload only when triggered by the insect's own biology. This shift toward green-synthesized, zero-residue solutions ensures that the high-tech fields are not only more productive but also fundamentally safer for the planet.

Conclusion

Nano-biotechnology is transforming pest control into a "search-and-destroy" mission for sustainable farming. The future lies in AI-driven precision by merging the power of gene-silencing "smart" delivery with eco-friendly material**s**, we are entering into a new era where the crops are protected by invisible, biodegradable shields that vanish once their job is done. This revolution endeavours for restoring the soil health, faster crop protection along with a high yielding future harvest while safeguarding the eco-equilibrium.

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