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Entomo-Pathogenic Nematodes (EPNs): The Yama of Insect Pests

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Recently, entomopathogenic nematodes (EPNs) have been recognized as the most efficient biological control tool in integrated pest management (IPM). By means of symbiotic interactions with bacteria like *Xenorhabdus* and *Photorhabdus*, these little soil-inhabiting insects provide a safe and green alternative for inorganic chemical pesticides. By specifically targeting insect pests, EPNs help to lower agricultural environmental impact without endangering the populations of other species. Since EPNs are known to be effective against many soil-dwelling and foliar insect pests, they offer a possible management tool for insect pest control. Here, we have focused on the biology, ecology and mechanisms of action, application methods and implications of the use of EPNs in sustainable agriculture. Additionally, we have reviewed the challenges with the commercialization and benefits of EPNs on a commercial scale and emphasize the need for more research to improve nematode efficacy in the field.

Recent improvements to combinations with other biocontrol agents, delivery systems, and formulations of entomopathogenic nematodes (EPNs) have helped to enable their practical use. The significance of EPNs for sustainable agriculture is becoming even more as climate change and resistance to chemical pesticides continue to threaten food security. This paper addresses the mechanisms, benefits, application strategies and topics for more investigation to maximize their use in contemporary agricultural systems.

Modern agricultural pest control relies mostly on synthetic chemical pesticides. Although their indiscriminate usage has raised major environmental and health issues, these herbicides have been absolutely vital in raising crop yields and lowering pest-related losses. Challenging issues like pesticide resistance, biodiversity loss, soil degradation and water pollution have driven scientists to investigate other pest management strategies that are both efficient and ecologically responsible (Yadav *et al.*, 2023; Singh *et al.*, 2024).

Using entomopathogenic nematodes (EPNs) as biological control agents against a wide range of insect pests is one encouraging strategy. EPNs, mostly from the families *Steinernematidae* and *Heterorhabditidae*, have shown efficacy in pest control in several agro-ecosystems. By means of a symbiotic interaction with bacterial partners, these nematodes infect and kill their host insects, hence offering an environmentally safe and focused method of pest control (Elbrense *et al.*, 2021; Li and Wu, 2024).

EPNs have shown great promise in agriculture, forestry and horticulture from their first effective use with Steinernema carpocapsae against the black vine weevil (Otiorhynchus sulcatus) (Koppenhöfer and Sousa, 2024). Growing interest in EPNs results from their selectivity to insect pests, low effect on non-target organisms and compatibility with current IPM approaches (Cummins, 2022; Crowther *et al.*, 2024). Their broad use has been hampered, meantime, by issues including environmental sensitivity, storage constraints, and application costs (Tomar and Thakur, 2022).

The biology, method of action, practical uses and possible developments of EPN technology in pest control are explored in this article. The conversation also emphasizes the need of more study to increase their effectiveness, provide affordable manufacturing methods, and include them into comprehensive pest management strategies.

What are Entomo-Pathogenic Nematodes?

EPNs are parasitic nematodes that specifically attack and kill insect pests by means of a certain symbiotic relationship with bacteria. The most extensively studied genera, *Steinernema* and *Heterorhabditis*, are widely used to target pest species across major insect orders, including Lepidoptera, Coleoptera, Hemiptera, Mantodea, Blattodea and Orthoptera.

Commonly used commercial EPN species include: *Steinernema carpocapsae*, *Steinernema feltiae*, *Steinernema riobrave*, *Heterorhabditis bacteriophora*, *Heterorhabditis marelatus*, *Heterorhabditis megidis*, etc. Naturally present in soil environments, these nematodes are crucial for managing subsurface insect pests including weevils and scarab larvae (white grubs).

Mechanisms of Action

EPNs are obligate parasites that infect and kill insect hosts through a tripartite interaction with their symbiotic bacteria. The process involves:

1. **Host Seeking and Penetration:** EPNs actively locate insect hosts by responding to chemotactic cues and penetrate through natural openings like the mouth, spiracles or anus (Kallali *et al.*, 2024). They release symbiotic bacteria after entering and then travel to the hemocoel of the insect.
2. **Bacterial Infection:** Symbiotic bacteria, such as *Xenorhabdus* in *Steinernema* and *Photorhabdus* in *Heterorhabditis*, rapidly multiply inside the insect's body, which produces toxins that cause

septicemia and death within 48-72 hours (Elbrense *et al.*, 2021; Li and Wu, 2024).

3. **Reproduction and Emergence:** The nematodes undergo numerous reproductive cycles within the insect cadaver; finally emerge as an infective juveniles (IJs) to seek new hosts and repeats the infection cycle (Cummins, 2022).

Advantages of EPNs in Pest Control

EPNs offer several benefits over chemical pesticides:

- Target Specificity: Minimal effect on non-target species, maintaining beneficial organisms including soil microorganisms and pollinators (Singh et al., 2024; Cummins, 2022).
- Environmental Safety: Unlike synthetic pesticides, EPNs are a safer choice for organic and sustainable agriculture, since they do not leave hazardous residues in the environment or build up in the food chain (Yadav et al., 2023).
- Resistance Management: By offering a substitute for controlling insect populations that have gained resistance to chemical pesticides, EPNs help to lower dependence on traditional pest management techniques (Tomar and Thakur, 2022).
- Long-Term Suppression: When included into IPM plans, some research indicate EPNs help to control long-term pests (Koppenhöfer and Sousa, 2024; Crowther et al., 2024).

Application Strategies

EPN efficacy depends on the application strategy. Common methods include:

- Inundative Releases: Large-scale applications for immediate pest control and management (Koppenhöfer and Sousa, 2024; Crowther et al., 2024).
- Inoculative Releases: Regular releases to create long-term populations that naturally survive in the soil environment (Javed et al., 2022).
- Formulation and Storage: To keep viability during transport and field application, EPNs are kept in substrates such as polyurethane sponge, gels or soil-based formulations.
- Combination with Other Controls: EPNs are often coupled with other biological agents, including as fungal infections and microbial insecticides, to boost their efficiency against insect pests (Crowther *et al.*, 2024).

Future Directions

To optimize EPN use, qualitative research must focus on:

- Enhancing Virulence: Genetic and formulation improvements to increase the pathogenicity and persistence of EPNs (Kallali et al., 2024; Li and Wu, 2024).
- Integrated Pest Management (IPM): Developing multi-faceted IPM strategies that integrate EPNs with crop rotation, habitat manipulation and companion planting (Crowther et al., 2024).
- Cost-Effective Production: Increasing economical production techniques to make EPNs more available to small-holder farmers (Cummins, 2022).
- Farmer Awareness: Expanding outreach initiatives to educate farmers on the benefits, proper storage and application techniques of EPNs.

Conclusion

EPNs offer a durable and efficient substitute for treatment of insect pests. Their capacity to target certain pests and their safety for non-target species makes them a useful tool in contemporary farming. To overcome constraints and achieve their potential in IPM, nevertheless, more research and development are still necessary.

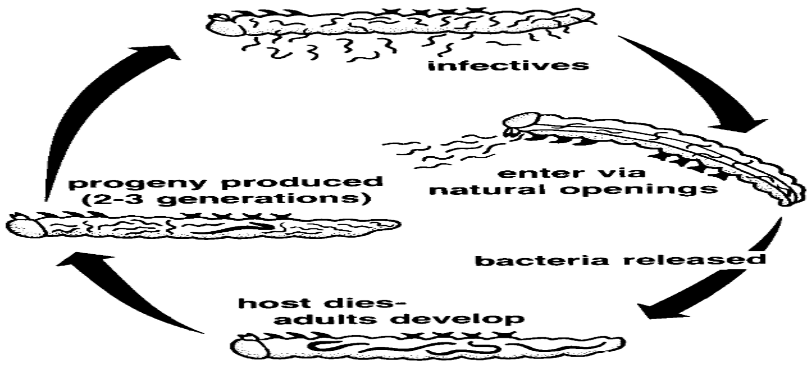

Figure 1: Life cycle of entomopathogenic nematodes

Table 1: List of EPNs used against the insect pests

Pest	**EPN Species**	**Efficacy (%)**	**Citation**
Potato Pests	*Steinernema feltiae*	96.3%	(Anorbaev *et al.*, 2024)
Turfgrass Pests	*Heterorhabditis bacteriophora*	67% reduction	(Koppenhöfer and Sousa, 2024)
Tobacco Cutworm	*H. bacteriophora*	90-96% mortality	(Tomar and Thakur, 2022)
Swede Midge	*H. bacteriophora*	59% reduction	(Crowther *et al.*, 2024)
Armyworm	*Steinernema pakistanense*	95% mortality	(Javed *et al.*, 2022)

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