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Nematode Management in Protected Cultivation

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Introduction

Protected cultivation refers to the growing of crops under controlled conditions (temperature, humidity, light, etc.) in structures such as greenhouses, high tunnels, and hydroponic systems. These systems provide an environment conducive to year-round production and increased crop yields. In spite of this protected environment infestation of insect-pests or nematodes is seen inside such structures which eventually may lead to significant losses if appropriate measures are not taken in time. The incidence and severity of nematode infestations is seen particularly high as such type of environment fosters their survival and reproduction. This makes them a significant concern for growers within these systems.

The management of nematodes in protected environments is somewhat complex due to the enclosed nature of these systems. Nematodes are known to inflict damage through root gall formation, feeding on plant tissues, and transmitting plant viruses, which directly impact crop productivity and quality. Therefore, effective nematode management strategies need to be devised which is crucial for sustainable agricultural production within these systems.

This article presents a detailed exploration of the types of nematodes found in protected cultivation, their symptoms, life cycles, impacts on crops, and management strategies under protected cultivation.

2. Nematodes in Protected Cultivation

Nematode Species of Concern

In protected cultivation systems, several nematode species are of economic concern. These species are categorized based on their feeding habits, the type of damage they cause, and the host plants they affect.

Some of the most common plant-parasitic nematodes in this aspect are:

- **Root-Knot Nematodes (*Meloidogyne* spp.):** These nematodes are among the most damaging and widespread, inducing the formation of characteristic galls on plant roots, impairing water and nutrient uptake. They are responsible for root galls that inhibit the plant's ability to take up water and nutrients. *Meloidogyne* spp. are polyphagous, meaning they affect a wide range of crops, including tomatoes, peppers, cucumbers, lettuce, and melons. Their ability to reproduce quickly and withstand varied environmental conditions makes them a common pest in greenhouses and tunnels.

- **Lesion Nematodes (*Pratylenchus* spp.):** These nematodes cause lesions on roots, disrupting the plant's vascular system, leading to decay and poor root development. These nematodes affect a wide range of crops, including potatoes, carrots, strawberries, and bananas. The symptoms they induce include root decay and wilting, particularly under high-moisture conditions.

- **Burrowing Nematodes (*Radopholus* spp.):** Known for their burrowing activity, *Radopholus* spp. create tunnels in plant roots, leading to extensive tissue damage and making them susceptible to secondary infections. They are particularly harmful to crops like bananas, papayas, and pineapples grown in greenhouses.

- **Cyst Nematodes (*Heterodera* spp.):** Although less common in protected cultivation, cyst nematodes can still pose a threat to specific crops like beans and potatoes under optimal conditions. These nematodes form cysts on roots, which can remain dormant in the soil for extended periods, making them difficult to manage.

2.1 Symptoms of Nematode Infestation

The symptoms of nematode infestation are often subtle at first but can escalate quickly with time. The symptoms of nematode infestation in plants are diverse and depend on the nematode species and the host plant. The symptoms can vary depending on the species involved and the plant being affected. However, common symptoms may include:

- **Stunting:** Nematodes feeding on the root system, impairs the plant's ability to absorb water and nutrients, which leads to overall stunted growth.

- **Wilting:** Plants infested by nematodes may show symptoms of wilting due to impaired water uptake from damaged roots despite adequate watering, and their overall productivity is diminished.
- **Root Decay and Rot:** Infected roots may begin to rot or decay, particularly in the case of burrowing nematodes (*Radopholus* spp.) that cause significant tissue breakdown.
- **Yellowing of Leaves:** Infected plants often exhibit interveinal chlorosis, particularly in cases of root-knot nematode infestations. This symptom is a result of nutrient deficiencies, particularly nitrogen and potassium due to damage to the roots.
- **Mottling of Leaves:** Some nematodes, such as *Meloidogyne*, are also associated with viral transmission, leading to mosaic-like mottling of leaves due to the spread of viral infections.
- **Secondary Infections:** Nematode-damaged plants are more susceptible to secondary fungal and bacterial infections due to the compromised root system, leading to more severe plant decline.
- **Galling:** The most characteristic symptom of *Meloidogyne* spp. is the formation of root galls. These galls are swollen, spherical growths on the root system, which interfere with the plant's ability to uptake water and nutrients, leading to further growth limitations.
- **Lesions:** Lesions caused by *Pratylenchus* spp. can lead to root decay, resulting in a dark, necrotic, rotted root system. This decay makes the plant more susceptible to secondary fungal infections, such as those caused by *Fusarium* spp.

2.3 Life Cycle and Impact of Nematodes

Nematodes undergo several developmental stages, including eggs, juveniles, and adults, with reproduction occurring either sexually or asexually, depending on the species. For example, in *Meloidogyne* spp., reproduction is typically parthenogenetic (asexual), meaning females can reproduce without mating. A single female can produce hundreds of eggs that hatch into juvenile nematodes, resulting in exponential population growth in a short time. The parthenogenetic reproduction in *Meloidogyne* allows for rapid population buildup, making it one of the most damaging and widely distributed plant-parasitic nematodes. In contrast, some other nematode species, such as *Pratylenchus* spp., reproduce sexually, with males and females mating to produce offsprings. This difference in reproductive strategies can significantly impact nematode population dynamics and management approaches.

3. Nematode Management Strategies

3.1 Cultural Control

Cultural control involves altering farming practices to reduce nematode populations and mitigate damage. The following practices are widely used in protected cultivation:

- **Crop Rotation:** Rotating crops (e.g., tomatoes) with non-host plants (e.g., beans, brassicas) can effectively reduce nematode populations in the soil, as many nematode species require specific host plants for their life cycle.
- **Intercropping:** Growing non-host plants in rotation can starve nematodes of their food source, thereby reducing their population over time. However, many crops grown in protected systems are often susceptible to nematodes, so careful selection of rotation crops is critical.
- **Sanitation:** Proper sanitation practices, including the removal of infected plant material, debris and weeds that harbor nematodes, are crucial for reducing nematode population build up.
- **Soil Solarization:** This technique involves covering the soil with transparent plastic to trap solar radiation and raise soil temperatures, killing nematodes and other soilborne pests. Soil solarization is particularly effective in areas with high temperatures and sufficient sunlight. It is particularly effective for managing *Meloidogyne* spp. and is an eco-friendly alternative to chemical fumigation.

3.2 Biological Control

Biological control agents provide sustainable alternatives to the use of chemical nematicides. It involves the use natural enemies of nematodes to control their population. Several biocontrol agents have been found promising in managing nematodes in protected cultivation:

- **Predatory Nematodes:** Species like *Heterorhabditis* and *Steinernema* spp. are entomopathogenic nematodes that parasitize and kill other nematodes. These can be applied to the soil or root zones as a biocontrol agent.

- **Nematophagous Fungi:** Fungi such as *Arthrobotrys* spp. and *Dactylaria* spp. are capable of trapping and killing nematodes. They form specialized structures like hyphal loops to capture nematodes.

- **Bacterial Agents:** Certain strains of *Bacillus* spp. and *Pseudomonas* spp. produce toxins that affect nematodes directly or inhibit their reproduction. These bacteria can be incorporated into the soil or applied as foliar sprays.

While biological control offers a promising alternative to chemical nematicides, its success depends on factors such as environmental conditions, nematode species, and different formulations of biocontrol agents.

3.3 Use of Nematode-Suppressive Plants

Nematode-suppressive plants play a significant role in nematode management. These plants have natural properties that inhibit nematode development or reduce their population in the soil.

- **French Marigold (*Tagetes patula*):** French marigolds are widely recognized for their ability to suppress nematode populations, particularly root-knot nematodes. They produce chemicals, such as thiophenes, that are toxic to nematodes. These compounds, particularly 2,4-dimethoxy-2,5-dihydrothiophene, have been shown to significantly reduce nematode eggs and juvenile development. Incorporating into rotation or intercropped with susceptible crops, marigolds can reduce nematode populations in the soil. Marigolds are easy to grow in protected environments, making them an excellent option for greenhouse production.

- **Other Suppressive Plants:** Other plants with nematode-suppressive properties include **mustard (*Brassica* spp.)**, which can be used as a biofumigant. Mustard plants release glucosinolates that break down into isothiocyanates, which have nematicidal properties. Additionally, certain species of ***Allium*** such as garlic and onions release volatile compounds, mainly, diallyl disulfide and allyl propyl disulphide respectively, which have been shown to be toxic to various nematode species. These plants release volatile compounds or natural biocides that can reduce nematode populations in the soil, thus enhancing crop productivity and contributing to sustainable pest management in protected systems.

3.4 Chemical Control

Chemical nematicides are traditionally the go-to solution for nematode management but have become controversial due to environmental concerns, resistance build up issues, and their impact on non-target organisms. The use of nematicides in protected cultivation is regulated, and alternatives are increasingly being sought.

- **Soil fumigants:** Chemicals such as methyl bromide, chloropicrin, and dazomet have been effective in controlling nematode populations. However, the phase-out of methyl bromide under the Montreal Protocol has led to the search for more environmentally friendly fumigants. Methyl bromide's widespread use, though effective, has been increasingly restricted due to its ozone-depleting potential, prompting the development of alternatives like **chloropicrin** and **dazomet**, which are more environmentally sustainable.

- **Non-fumigant nematicides:** These include materials such as abamectin, oxamyl and fluensulfone, which can be applied to the soil or as foliar treatments. Although they offer effective control, their use is often limited due to concerns over residue buildup and toxicity. Abamectin, for example, is effective against root-knot nematodes but can present challenges related to residues in food crops and its toxicity to beneficial organisms in the soil.

Integrated approaches often combine cultural, biological, and chemical methods to provide a more sustainable solution to nematode management.

3.5 Physical Control

Physical methods, such as soil heating and steam sterilization, are also effective for managing nematode populations. Soil heating involves raising the soil temperature to levels lethal to nematodes, typically through the use of solar energy or electric heaters; while steam sterilization directly applies steam to the soil to destroy nematodes and other pathogens. These methods are effective but often costly and labor-intensive. Physical methods involve altering environmental factors to make the habitat less conducive to nematode survival:

- **Soil Heating:** High temperatures can kill nematodes, and soil heating systems (e.g., steam sterilization) are employed in some protected systems. This method is effective in reducing nematode populations but is often labor-intensive and costly.

- **Nematode Traps:** These are physical devices or materials that attract and capture nematodes, thereby reducing their numbers in the soil.

- **Soil Draining:** In regions where, nematode problems are exacerbated by excess moisture, soil drainage can help reduce the prevalence of nematodes by creating less favorable conditions.

3.6 Application of Botanicals

Botanical control methods are gaining popularity due to their environmentally friendly nature and effectiveness in suppressing nematode populations. Botanicals work through multiple mechanisms, such as disrupting nematode life cycles, inhibiting egg hatch, or directly killing nematodes. The application of botanicals is especially valuable in integrated pest management (IPM) systems where chemical control is minimized.

- **Essential Oils:** Essential oils from plants like *Eucalyptus*, *Thyme*, *Clove*, and *Peppermint* have been shown to have nematicidal effects. These oils contain compounds such as eugenol and thymol that disrupt the nematode's nervous system or metabolism, leading to nematode mortality. For example, essential oils from *Cinnamomum* ***zeylanicum*** have been found to significantly reduce root-knot nematode populations in greenhouse tomatoes.

- **Plant Extracts:** Several plant extracts have demonstrated nematicidal properties. Extracts from *Allium* species (garlic, onion) are known to inhibit nematode hatching and reduce their population in the soil. Similarly, extracts from *Neem* (*Azadirachta indica*) are highly effective against nematodes by interfering with their reproduction and movement. Neem oil, for instance, is commonly used to manage root-knot nematodes in both soil and hydroponic systems.

3.7 Use of Resistant Cultivars

Genetic resistance to nematodes offers a long-term, sustainable approach to manage nematode infestations. Resistant varieties of crops like tomatoes, peppers, cucumbers and strawberries have been bred to withstand nematode infestations by either preventing nematode feeding or reducing their reproduction, making them valuable tools for sustainable nematode management in protected cultivation.

- **Root-Knot Nematode Resistance:** The development of *Meloidogyne*-resistant varieties has been a major focus in nematode-resistant breeding programs. Varieties of crops like tomatoes and peppers have been developed with resistance to *Meloidogyne* spp. Resistance is typically conferred by genes that prevent nematode penetration or gall formation. Resistance in tomatoes, for instance, has been associated with the Mi gene, which confers resistance to root-knot nematodes.

- **Lesion Nematode Resistance:** While resistance to lesion nematodes is more difficult to achieve but has led to some successful cultivars, particularly in potato and strawberry crops.

Genetically modified crops, including those with nematode resistance, may be a potential future avenue for nematode management, although they raise regulatory and market acceptance issues.

4. Integrated Pest Management (IPM)

An integrated pest management approach is essential for sustainable nematode control in protected cultivation. IPM combines multiple strategies to manage nematodes in a way that is both effective and sustainable focusing on minimizing environmental and economic impacts. Key principles of IPM include:

- **Thresholds for Action:** Economic thresholds can guide when to implement control measures, preventing over-reliance on chemical treatments, ensuring that resources are allocated effectively. Action is only taken when nematode populations reach a level where they are likely to cause significant crop damage.

- **Integrated Control:** Combining multiple control methods (e.g., using biocontrol agents along with crop rotation) can provide better results than any single method.

- **Monitoring:** Regular soil and root sampling allows for early detection of nematode infestations, enabling timely intervention and guides management decisions.

- **Combination of Control Methods:** IPM employs a combination of cultural, biological, and chemical methods to manage nematode populations in a balanced and environmentally responsible manner.

Some of the examples of application of integrated methods in controlling nematodes are as follows: -

- The combination of abamectin (*Streptomyces avermitilis*) and/or emamectin benzoate with *Purpureocillium lilacinum* and rhizobacteria (*Pseudomonas* and *Serratia*) was the most effective against *Meloidogyne incognita*, followed by rhizobacteria and *P. lilacinum*, not only in decreasing galls and reproduction of *M. incognita* but also in increasing growth of tomato plants. It was concluded that the application of various bioagents including abamectin might be a potential antagonism strategy against phytonematodes in protected agricultural areas.

- Management of burrowing nematode *Radophilus similis* was carried out by integrating eco-friendly components such as oil cakes (viz., castor, karanj and neem) and endomycorrhiza, *Glomus mosseae*. It was found that Karanj cake+ *G. mosseae* was most effective in increasing plant growth and fruit yield whereas neem cake+ *G. mosseae* was found to be effective in reducing the nematode population both in soil and roots. Mycorrhizal root colonization and number of chlamydospores of *G. mosseae* were found to be maximum in neem cake amended soil.
- Field experiments were carried out to study the efficacy of different biological control agents in controlling certain plant-parasitic nematode species such as *Meloidogyne javanica*, *Tylenchorhynchus mediterraneus*, *Hoplolaimus seinhorsti*, *Longidorus latocephalus*, and *Xiphinema elongatum* on guava and fig trees under the tropical field conditions of Jazan region, south-west Saudi Arabia. The evaluated bio-agents were used in different integrated management combinations of certain fungal species (*Trichoderma harzianum*, *Verticillium chlamydosporium*, and *Purpureocillium lilacinum*), the bacterium *Pasteuria penetrans*, some organic amendments (cow manure, compost, and chicken manure), urea 46% as a nitrogenous fertilizer, and the nematicide carbofuran 10G for comparison. Carbofuran 10G was found to be the most effective treatment in suppressing the nematode densities on guava and fig trees. The most effective management combinations, next to carbofuran 10G, in suppressing the nematode densities in the rhizosphere of guava trees were *P. lilacinum* + *P. penetrans* + urea 46%, *P. lilacinum* + *P. penetrans* + chicken manure, and *T. harzianum* + *P. penetrans* + chicken manure (66.54–69.22% nematode reductions). Correspondent combinations in the rhizosphere of fig trees were *P. lilacinum* + *P. penetrans* + cow manure, *T. harzianum* + *P. penetrans* + cow manure, *P. lilacinum* + *P. penetrans* + urea 46%, and *V. chlamydosporium* + *P. penetrans* + urea 46% (54.68–57.17% nematode reductions). All the tested treatments significantly also increased the number of fruits on guava and fig trees.

5. Challenges and Future Directions

Despite the significant advancements in nematode management, there are still several challenges:

- **Resistance Development:** Continuous reliance on a single method (such as chemical control) can lead to resistance development in nematode populations, necessitating the development of new control strategies.
- **Economic Constraints:** The implementation of IPM strategies can be costly for small-scale growers, especially when specialized biological control agents and resistant cultivars are not readily available.
- **Environmental Concerns:** The growing regulation environmental impact of chemical control measures, particularly fumigants, makes it essential to find environmentally safer alternatives.
- **Research Gaps:** Further research is needed to identify new nematode species, improve biocontrol options, and develop more effective nematode-resistant cultivars.

Future research should focus on:

- **Genetic Innovations:** Further development of resistant cultivars and the exploration of genetically modified crops.
- **Advanced Biocontrol Methods:** Identification of new nematode predators, parasites, and symbiotic organisms for more effective biological control.
- **Improved Monitoring Techniques:** Enhanced diagnostic tools for early nematode detection and population monitoring.

Future research will likely focus on enhancing genetic resistance, developing more effective and targeted biocontrol agents, and improving integrated control strategies. Advanced technologies such as precision agriculture, which uses sensors and data analytics, may also help in optimizing nematode management by allowing for more precise control measures.

6. Conclusion

Effective nematode management in protected cultivation systems is a complex challenge that requires an integrated, multifaceted approach for sustainable crop production. While challenges remain, an integrated pest management approach combining cultural, biological, chemical, and physical control methods offers a promising solution. Ongoing research into resistance breeding, biocontrol agents, and novel monitoring techniques will continue to drive innovation in nematode management practices, providing growers with the tools they need to manage nematodes in protected environments. With the adoption of holistic approach, the agricultural industry can better manage nematode infestations in a way that promotes both long-term environmental sustainability and economic viability.