

INTEGRATED NEMATODE MANAGEMENT (INM)

Abstract

Integrated Nematode Management (INM) is a set of strategies aimed at controlling nematode populations in agricultural systems. Nematodes are microscopic, worm-like organisms that can cause damage to crops, and their control is important for sustainable and profitable agricultural production. INM involves combining different control methods in a coordinated way to manage nematode populations while minimizing the negative impact on the environment. The components of INM typically include cultural practices, such as crop rotation and the use of resistant varieties, biological control, such as the use of natural enemies of nematodes, and chemical control, such as the use of nematicides. The goal of INM is to use these different approaches in a complementary manner so that each method enhances the effectiveness of the others while minimizing the overall impact on the environment. For example, a farmer might use crop rotation to break the life cycle of nematodes, followed by the use of nematode-resistant crop varieties to reduce nematode damage. In addition, the farmer might introduce beneficial nematodes or other natural enemies to control nematode populations and use chemical control only when necessary and with minimal environmental impact. Overall, INM is an important approach for managing nematodes in agricultural systems, as it allows farmers to reduce nematode populations while minimizing the negative impact on the environment and maintaining the sustainability of their agricultural systems.

Keywords: INM Ectoparasites, Semi-Endoparasites,

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I. DEFINITION OF INTEGRATED NEMATODE MANAGEMENT

A methodical strategy to lower the nematode population using a variety of methods, such as chemical nematodes when needed, cultural, mechanical, physical, biological, and genetically resistant hosts, and natural environmental alterations.

II. INTRODUCTION

Nematodes are thought to be responsible for crop yield losses of more than US\$ 78 billion globally. In underdeveloped nations, these losses are estimated to be over 14%, while in developed nations, they are over 9%. Compared to temperate locations, tropical regions experience far more damage from nematodes. The cultivator employs a variety of strategies to stop the spread of harmful nematode populations. These management methods can be applied with the least number of nematodes in situations when an advisory service is set up to keep an eye on field populations. Integrated nematode management is difficult without advising services, and chemical nematodes are used in relatively high dosages. The perceived worth of the possible crop loss and the expense of the management process are taken into consideration when deciding whether to conduct nematode management initiatives. When the marginal revenue from the management input equals or surpasses the marginal cost, management procedures should typically be put into place. INM aims to achieve the following goals:

III. OBJECTIVES OF INM

1. To minimize environmental and health hazards
2. Utilization of several compatible measures
3. To maximize natural environmental resistance to plant parasitic nematodes
4. To minimize the use of drastic control measures and also to minimize the input costs
5. To increase reliance on location-specific and resource-compatible management strategy

IV. TYPES OF NEMATODES ON THE BASIS OF FEEDING SITE

1. **Ectoparasites:** The nematodes remain outside of the host and use their stylet to feed from the cells of the host roots.
2. **Semi-Endoparasites:** Nematodes partially penetrate the host and feed at some point in their life cycle.
3. **Migratory Endoparasites:** Nematodes spend much of their time migrating through root tissues destructively feeding on plant cells.
4. **Sedentary Endoparasites:** Nematodes in the J2 stage attack plants close to the root tip and move through the root tissues in growing vascular cells. In the early stages of development, these worms are fully lodged in the root; however, later on, the cyst nematodes emerge from the root.

Genera of the Most Common Plant Parasitic Nematodes

S. No.	Name of Nematode	Zoological Name
1.	Root-knot nematode	<i>Meloidogyne incognita</i> , <i>M. javanica</i> , <i>M. hapla</i> , <i>M. arenaria</i> , <i>M. graminicola</i> and <i>M. indica</i>
2.	Citrus nematode	<i>Tylenchulus semipenetrans</i>
3.	Potato cyst nematodes	<i>Globoderarostochiensis</i> and <i>G. pallida</i>
4.	Rice root nematode	<i>Hirschmanniella</i> spp.
5.	Wheat seed gall nematode	<i>Anguinatritici</i>
6.	Cyst nematodes	<i>Heteroderazeae</i> and <i>H. cajani</i>
7.	Lesion nematode	<i>Pratylenchus coffeae</i> , <i>P. indicus</i> , <i>P. thornei</i> and <i>P. zaeae</i>
8.	Ufra nematode	<i>Ditylenchus angustus</i>
9.	White tip nematode	<i>Aphelenchoides besseyi</i>
10.	Burrowing nematode	<i>Radopholus similis</i>

V. GENERAL PRINCIPLES OF INM

- 1. Avoidance:** Planting when or where inoculum is scarce or nonexistent, or when environmental factors render it ineffective, can help prevent disease. Nematode dispersal mechanisms include soil movement through machinery and plant parts, agricultural transplants, water, animals, and infected containers like hessian bags. Programmes for national or regional nematode IPM should include precautions against the spread and creation of new nematode issues.
- 2. Proper Selection of Geographical Area:** There are numerous variables that can affect a nematode species' spread. Distribution could be the result of a very recent introduction to a new area or a long-standing relationship with native plants. Crops free of illness can be produced by selecting a certain geographic location that is devoid of a specific nematode. Therefore, minimising nematode infestation will also depend on the geographic location chosen.
- 3. Selection of Planting Site:** Although nematodes are thought to be common throughout nature, there are several areas where pathogenic nematodes are either nonexistent or present at very low levels. These regions are typically recognised as being free of disease. For the import and export of germplasms/seeds and seedling materials, these places are preferred by the plant quarantine regulations. Ex: Because the Nilgiri Hills of India are devoid of cyst nematodes, potato producers choose to accept potato seeds grown elsewhere in the country the most. Sites devoid of harmful nematodes are excellent, particularly for harvests of vegetables and flowers that are highly appreciated. Many commercial producers in the Netherlands favour growing vegetables and orchids in nematode-free environments. Preventing the entry of lesion nematodes into a field is the optimal approach to managing them. The greatest defence against lesion nematode issues is to select a field site that is not affected.

4. **Adjusting the Time of Sowing/Planting:** Changing the timing of sowing or planting helps prevent nematode damage because the destructive activity of worms is dependent on environmental variables. Since nematodes cannot survive in cold temperatures, some crops are sown or planted during the winter, when the soil temperature is lower. During the cold season, early potatoes and sugar beets develop because the cyst nematode is less active and damages the crops.
5. **Proper Selection of Seed and Planting Material:** Using sections of healthy plants, we can eradicate nematodes from plants grown vegetatively. Choosing planting materials free of nematodes can help eradicate the golden nematode that attacks potatoes and the lesion nematode that attacks bananas. Using nematode-free seeds will help manage the rice white tip and wheat seed gall nematodes.

VI. EXCLUSION

The aim of this principle is to prevent the contact between the pathogen and seed materials/planting materials in the field, i.e., to prevent spread of the disease. These measures aim to prevent the inoculum from entering or establishing in the field or area where it does not exist.

Dissemination and establishment of plant parasitic nematodes can be prevented through exclusion procedures. Dissemination includes the movement of soil on equipment and plant parts, crop transplants, water, animals, and contaminated containers such as burlap bags, etc. Exclusion procedures include sanitation, certification of seeds and plant material, nematode-free soil, reduction of nematode population, eradication procedures, and regulatory activities. Different valuable exclusion procedures are given below.

1. **Inspection, Certification, and Quarantine:** Nematode propagation materials and infected seeds are the main ways that nematodes spread. They frequently have soil on them, and moving cars are dangerous as well. Prior to seeding, the field should be inspected to ensure that no nematode-infested seeds, planting material, or plot are used. Examining areas free of pests not only facilitates the production of high-quality seeds but also lowers the risk of nematode migration by focusing on export-oriented items. The approved authority must check, test, and certify the seed lot to ensure it is free of PCN. In every state, seed manufacturers and growers who offer seed derived from commercial crops ought to be registered under approved programmes. In potatoes, Potato Cyst Nematode (PCN) is a major issue. In Australia, it is against the law to cultivate or sell seed potatoes for commercial purposes without certification.

Nematodes should not be allowed to enter a region that is not infected in order to prevent the nematode from spreading. This is one of the fundamental ideas of quarantine. Traditionally, quarantine laws have been used to limit the entry of contaminated soil and plant materials into a state or nation. Many nations keep complex networks in place to thwart plant exports that include pests like nematodes.

2. **Education for Growers:** There is very little knowledge on nematode damage to crops among extension agents and farmers. The farmers should be shown the advantages of

controlling nematodes and the harm they cause, together with information from the extension personnel.

- 3. Restriction of Nematodes Spread:** Water runoff, seeds, planting materials, and contaminated soil are the main ways that nematodes spread. A field's perimeter, irrigation water runoff, custom tillage, flood water tillage activities, land levelling, contaminated soil sticking to cars and harvesting equipment can all contribute to the rapid spread of nematodes. Root-knot nematodes spread with infested planting tubers or root parts which do not show symptoms. So sanitation and good cultural practices are the best preventive methods against nematode spread.

VII. CULTURAL PRACTICES

Various cultural practices are much helpful to prevent the spread of the nematode population which are adopted by the growers. Such as fallowing, flooding, cover crops, crop rotation, roguing of infested hosts, antagonistic crops, cleaning of planting stocks, nutrients and water management, resistant cultivars, etc. Therefore, there is a gradual shift towards the concept of management of the nematode population instead of eradication.

- 1. Summer Ploughing:** In order to expose the nematodes and afflicted tissues to solar heat and dehydration, two to three deep summer ploughings should be performed in May and June. The number of root-knot nematodes is decreased by this technique. According to Jain and Bhatti (1987), this method works well for controlling root-knot nematodes. According to Singh (2013), *M. incognita* was greatly decreased in brinjal by fallowing and summer ploughing throughout the hot summer months. According to Jain and Gupta (1990), at the time of transplanting, the root-knot nematode population was significantly reduced, ranging from 78.2 to 92.3%, depending on whether normal (10 cm) or deep (20 cm) ploughing was performed in June and was followed by a fallow period of roughly two months.
 - **Fallowing:** For longer than a few weeks, the majority of nematodes require both a host and moisture to survive. Therefore, reducing the nematode population would involve leaving the field fallow for different lengths of time.
 - **Flooding:** Maintaining the land submerged in water reduces the amount of oxygen in the soil and asphyxiates the worms. Although the method may not be cost-effective, it works well to prevent root knot and stunt nematodes on vegetables.
 - **Trap Crops:** Usually sown in regions with nematode infestations, trap crops are exceedingly delicate plants. While other crops, including *Crotalaria spectabilis*, do not promote the establishment of root-knot nematodes, they do allow their invasion.
- 2. Cover Crops:** Green manures decompose to release nematotoxic chemicals, which suppress the nematode population (Chitwood and David 2002). Generally speaking, nematode treatment with cover crops has been successful when using *Crotalaria*, castor bean, velvet bean, jack bean, sorghum-Sudan, castor, grasses, and cereals (Hackney and Dickerson 1975; Viaene et al. 2006).

3. **Crop Rotation:** Growing a non-host crop in between two sensitive hosts lowers the pathogenic nematode population and lowers the harm threshold in crop rotation. The best method for controlling diseases like Molya, which is brought on by *Heterodera avenae* in wheat, is crop rotation. To grow a successful wheat harvest, grow non-hosts such as mustard, gramme, etc. for a period of one to two years. This will significantly reduce the population of *H. avenae*. A fundamental tenet of this approach is malnutrition and disruption of their life cycle. Revolving non-host crops such cereals, onions, garlic, nematodes, and velvet beans (*Mucuna*) for a minimum of two to three years in an appropriate farming strategy reduces the nematode inoculum level (Alam and Siddiqui (2001)).
4. **Roguing and Destruction of Infested Host:** Weeds including *Chenopodium album*, *Solanum nigrum*, *Tithonia rotundifolia*, and other unidentified weeds that are known to be connected to vegetables and other crops that serve as nematodes' alternate hosts for the duration of their life cycle should be removed and burned. (Khan and others, 2014). Similar to this, when the rice grains are harvested, *Ditylenchus angustus* stays in the field's leftover stubbles. As soon as possible, such stubbles should be cut off and eliminated.
5. **Antagonistic Crops (Bio-fumigation):** Antibiotic crops are those that, by the release of harmful chemicals, inhibit the growth and development of another microbe. Plant antagonistic crops between susceptible primary crops, such as African marigold, mustard, and asparagus, to help suppress the population of root-knot nematodes. Growing African marigold (*Tagetes erecta* or *T. patula*) alongside sensitive crops releases nematotoxic chemicals such as polyterthienyl (α -terthienyl) through root exudates, hence decreasing the population of root-knot nematodes. Reproduction of nematodes is inhibited by adding Brassica spp. as green manures to the soil, such as Indian mustard (*Brassica juncea*) and rapeseed (*B. napus*). They break down to yield volatile molecules that are extremely toxic to nematodes, such as isothiocyanates, which are made from glucosinolates.
6. **Clean Planting Stock:** Selecting the vegetative portion of healthy plants is one way to eradicate nematodes from plants grown by vegetative techniques. If nematode-free plant materials are chosen, nematodes such as the spiral, lesion, and burrowing nematodes of bananas and potatoes can be eradicated. By utilising nematode-free seeds, the rice white tip and wheat seed gall nematodes can be managed safely (Maurya et al., 2018).
7. **Nutrient and Water Management:** It might also be crucial in reducing agricultural damage brought on by worms that parasitize plants. Some plants may be able to withstand high nematode populations if there are enough potassium levels in the soil. It has been demonstrated that ammonium sources of nitrogen reduce a variety of nematodes, such as *Heterodera glycines*, the soybean cyst nematode. When it comes to lucerne nematodes, high calcium levels may strengthen the host's defences against *Ditylenchus dipsaci* (Maurya et al., 2020).
8. **Use of Organic Amendments:** In order to demonstrate strong nematicidal activity and even prevent phytotoxicity on crops, organic amendments with C:N ratios between 12 and 20 were found to be extremely appropriate. Neem leaf, seed kernel, seed powders, seed extracts, oil, sawdust, and oilcake are examples of plant products that have been widely utilised to combat the control of nematodes that cause knotting in roots, as well as

other significant plant parasitic nematodes. The release of chemical components from neem, including salanin, azadirachtin, nimbin, thionemone, and other flavonoids, is responsible for the nematocidal effect.

- 9. Resistant Cultivars:** The greatest methods for managing nematodes in an environmentally safe manner are resistant cultivars. According to Roberts (2002), resistance in nematology refers to a plant's capacity to inhibit the growth or reproduction of nematodes. The table below lists the sources of resistance in solanaceous and other plants.

S. No.	Crops	Parasites	Resistant Cultivars
1.	Tomato	<i>Meloidogyne incognita</i>	HisarLalit and IIHR 2868
2.	Chilli	<i>Meloidogyne incognita</i>	PusaJwala and White Kandhar
3.	Potato	Potato cyst nematode	KufriSwarnaKufriNeelima

- 10. Biological Control:** The greatest substitute method for managing nematodes is thought to be the use of bio-control agents. Nematode management made simple, safe, and less expensive with the use of bio-control agents to lessen the amount of chemical residue in vegetable crops. In order to control plant parasitic nematodes, the primary goal of biological management of nematodes is to influence nematode parasites, predators, and pathogens in the rhizosphere.

Numerous bacteria and fungi, including *Aspergillusniger*, *Paecilomyceslilacinus*, *Trichodermaviride*, *T. harzianum*, and *T. harzianum*, have also been reported to inhibit reniform and root-knot nematodes. Nematodes with root knots can be suppressed by the bacteria *Pasteuriapenetrans*. It has also been discovered that an Indian strain of *P. penetrans* is able to inhibit the nematodes that cause pigeon pea cysts (Pant *et al.*, 2023).

VIII. FUNGAL ANTAGONISTS

- 1. Nematode Trapping Fungi:** Two types of fungi known as fungal antagonists, *Arthrobotrys* spp. and *Monacrosporium* spp., respectively, trap nematodes in constricting rings and adhesive nets. The connection between a lectin released by the fungus and a carbohydrate secreted by the worm cuticle is their mode of predation. But only select nematode species are targeted by their predation, and these antagonists' limited distribution in soil restricts their possible use. [Manjunatha and others, 2017].
- 2. Egg Parasites:** *Paecilomyceslilacinus*1% W. P. and *Pochoniachlamydosporia*1% W. P. are effective bionematicides. *P. lilacinus*and *P. chlamydosporia*are the potential fungal antagonists successfully control by parasitizing eggs and females of root-knot nematode. (IIHR, Bengaluru)
- 3. Toxin-Producing Fungi:** Some fungi produce toxins that have antagonistic effects against plant parasitic nematodes such as *Aspergillus*spp. (*Aspergillusniger*, *Aspergillusflavus**Aspergillus fumigates*and *Aspergillusterreus*), *Trichoderma*spp. (*Trichodermaviride*, *Trichodermaharzianum*),*Rhizoctoniaabataticola*, *Alternariaalternata*,*Penicilliumchrysogenum*. Most prominently the filamentous fungi,

Trichoderma harzianum 1% *W. P.* & *Trichoderma viride* 1.5% *W. P.* strains are commercially used for the management of root-knot nematodes infesting vegetable crops, and the effective bio-fungicides. (IIHR, Bengaluru).

4. **Bacterial Antagonists:** This group is categorized into two major groups viz., Nematode parasites (*Pasteuriapenetrans*) and Nematode antagonistic rhizobacteria.
5. ***Pasteuriapenetrans*:** It is an obligate parasite that produces an adhesive endospore that inhibits reproduction activity in the root-knot nematode.
6. **Nematode Antagonistic Rhizobacteria:** Plant Growth Promoting Rhizobacteria (PGPR) has four multiple modes of action such as-
 - Competition
 - Antibiosis
 - Plant growth promotion
 - Induction of systemic resistance against plant parasitic nematodes

Numerous host plant species are infected by bacterial diseases; nevertheless, *Pseudomonas fluorescens* 1% *W. P.* is a potent bioagent with nematicidal capabilities. The high nematicidal activity of *P. fluorescens* strain is caused by the antibiotic DAPG (2, 4-diacetyl phloroglucinol) characteristic. Therefore, strains that produce the antibiotic DAPG have been routinely employed to combat root-knot nematodes that infect crops and vegetables. *Bacillus* spp. is another promising nematode antagonist in PGPR. The most promising antagonists are *Bacillus* species, such as *Bacillus subtilis* and *B. pumilus*, which create secondary toxic compounds that reduce the nematode population.

7. **Conservation:** The most successful application of biological control over nematodes has been the preservation and amplification of naturally occurring antagonists in the soil. *Heterodera avenae*, the cereal cyst nematode, is effectively suppressed in England by cultivating monocultures of tiny grains that sustain the high biomass of specific nematophagous fungus.

IX. PHYSICAL METHODS

Although it is very simple to kill nematodes in a lab setting by subjecting them to heat, radiation, osmotic pressure, etc., implementing these techniques in a field setting is quite challenging. Physical approaches are a small but significant class of procedures that are usually used either independently or in conjunction with chemical and cultural management strategies.

1. **Soil Solarization and its Principle:** It is a method of heating moist soil by covering it with 100 gauge Linear Low-Density Polyethylene (LLDPE) clear films that were efficient to manage nematode incidence.
 - Accumulation of heat due to transmission of short-wave solar radiation and prevents loss of long-wave radiation in solarized soil
 - Increase in temperature due to the greenhouse effect
 - Soil moisture helps in the solarization process by conducting heat energy

- Increase in microbial and physicochemical reactions in the soil resulting in accumulations of gases, some being toxic pathogens and others acting as a nutrient source or inducing resistance to subsequent crops
- Prolonged exposure to higher temperatures resulting in increased mortality of nematodes and also making them susceptible to antagonists

According to Jain and Gupta (1996), solarization in May and June decreased the population of *M. javanica* soil nematodes by 78%. According to Jain and Gupta (1997), soil solarization in the nursery with clear and black LLDPE mulch decreased 92.5 and 87.4% of the soil population of *M. javanica*, respectively. According to Walia *et al.* (2016), applying 100 gauzes (25 µm) of LLDPE clear plastic film to the soil for 15 days in May reduced the amount of weeds and root-knot disease by 93% and 66%, respectively.

- 2. Steam Sterilisation:** Steam cleaning is not a common practise. It is one of the most effective and manageable methods for reclaiming soil, but it requires expensive facilities. When growing flowers and vegetables under protection, steam sterilisation is used in greenhouses and ploy houses.
- 3. Hot Water Treatments:** Since at least the early 1900s, hot water treatments of planting stock have been used in practical nematode management programmes. Before planting, seed materials such onion bulbs, banana corms, tubers, and seedling roots can be soaked in hot water at 50 to 55 °C for ten minutes.

Hot Water Treatment for Control of Nematode in Planting Material:

S. No.	Propagating Materials	Parasitic Nematodes	Temp. (°C)	Time (min.)
1.	Banana sucker	<i>M.incognita</i> and <i>R.similis</i>	55	20
2.	Grape root stock	<i>Meloidogynespp.</i>	52.7	05
3.	Ginger rhizome	<i>Meloidogyne spp.</i>	45-55	10-50
4.	Wheat	<i>Anguinatritici</i>	54-56	10-12

X. MANAGEMENT THROUGH CHEMICALS (NEMATOCIDES)

It is advised to utilise nematodes only in situations where the crop is valuable, rapid results are required, and worm populations are extremely high. The following section discusses the various options and methods that can be used to make the usage of nematicides safer and more economically viable. Fumigants and non-fumigants are the two basic groups into which nematodes can be divided.

- 1. Fumigants:** Chemicals known as "soil fumigants" are injected into the soil to produce poisonous fumes that pierce the soil's air gaps and kill nematodes. To guarantee a fatal concentration and exposure duration, fumigants need to be submerged in the ground using water or a plastic sheet. Nematodes can be controlled with the majority of pre-plant fumigants, including dichloropropene, chloropicrin, and metam-sodium (Busan, Nemasol, Vapam).When the soil has moderate moisture content and temperatures vary between 20°C and 30°C at a 6-inch depth, it is the best time to fumigate. Exercise CAUTION

when performing pre-plant fumigation in the spring. Certain fumigants have the potential to persist in damp, chilly soils, increasing the risk of harm to immature plants. Fields should be irrigated to raise the soil moisture content to a suitable level if it is low.

2. **Non-Fumigants:** Certain crops can be treated with a variety of nonfumigantnematicides, also referred to as systemic nematicides. The fumigants volatilize in the soil, whereas these nematicides do not. For these compounds, soil temperatures and moisture needs are therefore less important. The following lists a few instances of carbamates and organophosphates: -

Organophosphates: -Phorate, Thionazin

Carbamates: -Aldicarb, Carbofuran

3. Application Methods:

- Carbofuran 3G @ 1-3 kg/ha (3-6g/sqm) should be used before sowing as a soil treatment.
- Carbosulfan 25 EC, dimethoate 30 EC @ 0.05 to 0.2% should be used for the soaking of seeds. The duration of treatment depends on the nature of the crop and it varies between 4-12 hrs.
- Foliar treatment: Systemic compounds such as carbosulfan, and monocrotophos can be used to control the nematode. Oxymyl @ (0.12%) at an interval of 15 days.

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