DOI: 10.21088/ijab.2454.7964.12126.7

Indian Journal of Agriculture Business
Volume 12 Number 1, January – June 2026

REVIEW ARTICLE

Plant Parasitic *Nematodes* are affecting Yield of Economically Important Crops

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HOW TO CITE THIS ARTICLE:

Amar Bahadur. Plant Parasitic *Nematodes* are affecting Yield of Economically Important Crops. J Agri Busi 2026; 12(1): 54–70.

ABSTRACT

Plant-parasitic nematodes are one of the greatest threats to crops worldwide. Plant-parasitic nematodes are microscopic worms that cause billions of dollars in crop losses annually. Belongs to the animal kingdom and can survive in any environment as the most important plant pathogen in agriculture, causing yield losses of crops worldwide. Nematode infection in the soil can lead to secondary infection with fungal and bacterial pathogens and even to the transmission of plant-infecting viruses. Vegetable crops are usually most susceptible to the nematodes. Plant-parasitic nematodes are small worms like transparent, bilateral symmetry, pseudocoelomate, multicellular, free-living or parasitic microorganisms which are predatory, aquatic, terrestrial, entomopathogenic, ectoparasite, endoparasite, semi-endoparasite. Plant-parasitic nematodes differ in their way of life. Ectoparasitic nematodes outside the host cells feed on plant roots while endoparasitic nematodes establish within plant tissue and are divided into migratory and sedentary groups. Migratory endoparasitic nematodes are *Pratylenchus* spp. *Radopholus* spp. and *Hirschmanniella* are economically important. Plant parasite nematodes are identified by stylet and sub-ventral and dorsal esophagous glands which plays a significant role. *Meloidogyne* spp. *Heterodera* spp. *Globodera* spp. and *Pratylenchus* spp. are important species and widely distributed throughout the world with a wide host range. Phytonematodes suppress host immune responses for the development of feeding sites. Plant-parasitic nematodes have hollow, needle-like, protrusible stylet to probe plant tissue and release proteinaceous secretions from the sub-ventral and dorsal glands, allowing for nematode entry. The economically important species target plant roots of crops and prevent water and nutrient uptake resulting in reduced crop yields. Nematodes damage the host plants by causing wounds on the plant roots forming brown spots, changing the physiology of the host, making them more vulnerable to being infected by other pathogens and leading to

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➤ **Received:** 31-10-2025 ➤ **Accepted:** 20-12-2025

environmental stresses. Once nematodes are introduced into an agricultural area, their eradication is difficult. Integrated management is recommended based on different practices to reduce soil nematode populations.

KEYWORDS

• Nematodes • Crops • Losses • Symptoms • Management

INTRODUCTION

Nematodes cause injury to the plants by direct damage, allow infection by another organism and interact with other pathogens, transmit pathogens, increase susceptibility to environmental stress, interfere with rhizobial nodulation in legumes and lead to a decrease in nodule number, size and nitrogen fixation. Nematode produces several types of symptoms on the host plant such as stunting, gall formation, tuber rot, stubby root, burrowing, white tip, chlorosis, root lesion etc. Nematode management is important because according to estimated plant-parasitic nematodes are causing much more damage annually compared to insect pests. They caused an estimated yield loss of 12.3 % ($157 billion) worldwide. Nematode diseases of crops are difficult to control as their hidden in nature. Plant-parasitic nematodes not only cause damage individually but form disease complexes with other micro-organisms and increased crop loss.[1] Plant-parasitic nematodes comprise serious threats to crop yield in quantity and quality globally. Damage caused by plant nematodes has been estimated at $80 billion per year.[2] They are responsible for 10% of global crop losses annually which is approximately US$173 billion per year.[3] Plant-parasitic nematodes are small, soil-borne pathogens and symptoms are appears often nonspecific. Plant-parasitic nematodes penetrate cells for feeding and entries for endoparasitic nematodes into the host interact with hosts through hollow, protrusible stylets. Some nematodes are migratory ectoparasites that simply migrate through the soil, migratory endoparasites enter the host and migrate in tissues causing extensive damage. Semi-endoparasitic nematodes have migratory stages, but penetrate the host plant to feed at one stage of the life cycle, such as *Rotylenchulus reniformis* feeding structure at the sedentary stage. The Plant-parasitic nematodes are the pests of a wide host range of agriculturally important crops, and their feeding habits are migratory, sedentary, ectoparasites and endoparasites with the host. Plant-parasitic nematodes have mainly been controlled by soil fumigants nematicides for decades but in recent years, several nematicides have been withdrawn from the market because they cause environmental pollution[4] and contaminate groundwater.[5] Resistant crop varieties through the breeding approach are time taking and R-gene sources are also limited, so transgenic plants with nematode resistance varieties are now developed with RNAi technology[6,7,8] and protease inhibitors.[9,10]

ECONOMIC LOSSES

Plant-parasitic nematodes are microscopic, invertebrate animals often called threadworms, eelworms, and roundworms; hidden enemies of crops and growers are unaware of crop losses. They are distributed all over the world in different habitats and found in nearly every place that supports life. They damage the crops by feeding on plants and interacting with various other organisms. Damage caused by nematodes is often confused with other causes such as a fungal attack, water stress, and physiological disorders. Nematodes cause about 14 % of global losses amounting to $100 billion annually.[11] Crops loss has been reported in quantitative, and qualitative, with an average crop loss of 12.6% ($215.77 billion) worldwide.[12] Nematodes cause severe losses to economically important crops like vegetables, cereals, pulses, oilseeds, and fruit crops[13] have crop loss due to phytonematodes on worldwide for $100 billion.[14] A worldwide survey was conducted and found that the 10 most important genera of plant-parasitic nematodes revealed were *Meloidogyne, Pratylenchus, Heterodera, Ditylenchus, Globodera, Tylenchulus, Xiphinema, Radopholus, Rotylenchulus* and *Helicotylenchus* causing damage to crops.[15] There are some reports which indicate heavy crop losses due to nematodes in India.[16] The economic important genus of nematodes and their common name is given in Table 1 and the relative size of nematodes[17] in Figure 1.

Table 1: Economic important genera of phytonematodes and their common name

Generic name	Common name
Meloidogyne spp	Root-knot nematode
Heterodera spp	Cyst Nematode
Globodera spp	Golden cyst nematodes
Pratylenchus spp	Lesion (meadow) nematode
Radopholus similis, R. citrophilus	Burrowing nematode
Hirschmanniella sp.	Rice root nematode
Tylenchulus semipenetrans	Citrus nematode
Rotynenchulus reniformis	Reniform nematode
Ditylenchus spp.	Stem and bulb nematode
Aphelenchoides spp.	Leaf and bud nematode
Anguina tritici	Wheat seed gall nematode
Aphelenchoides ritzemabosi	Foliar nematodes
Aphelenchoides besseyi	White tip nematode
Hemicycliophora sp	Sheath nematode
Criconema, Criconemoides	Ring Nematode
Heliotylenchu, Rotylenchus	Spiral nematode
Hoplolaimus spp	Lance nematode
Longidorus spp	Needle nematode
Xiphinema sp	Dagger nematode
Trichodorus, Paratrichodorus	Stubby root nematode
Rhadinaphelenchus cocophillus	Red ring nematodes
Bursaphelenchus xylophilus	Pinewood nematode
Nacobbus sp.	False root-knot nematode
Paratylenchus spp.	Pin Nematode
Tylenchorhynchus spp.	Stunt, stylet nematode
Belonolaimus spp.	Sting nematode
Hemicriconemoides spp.	Sheathoid nematode
Cacopaurus pestis	Sessile nematode

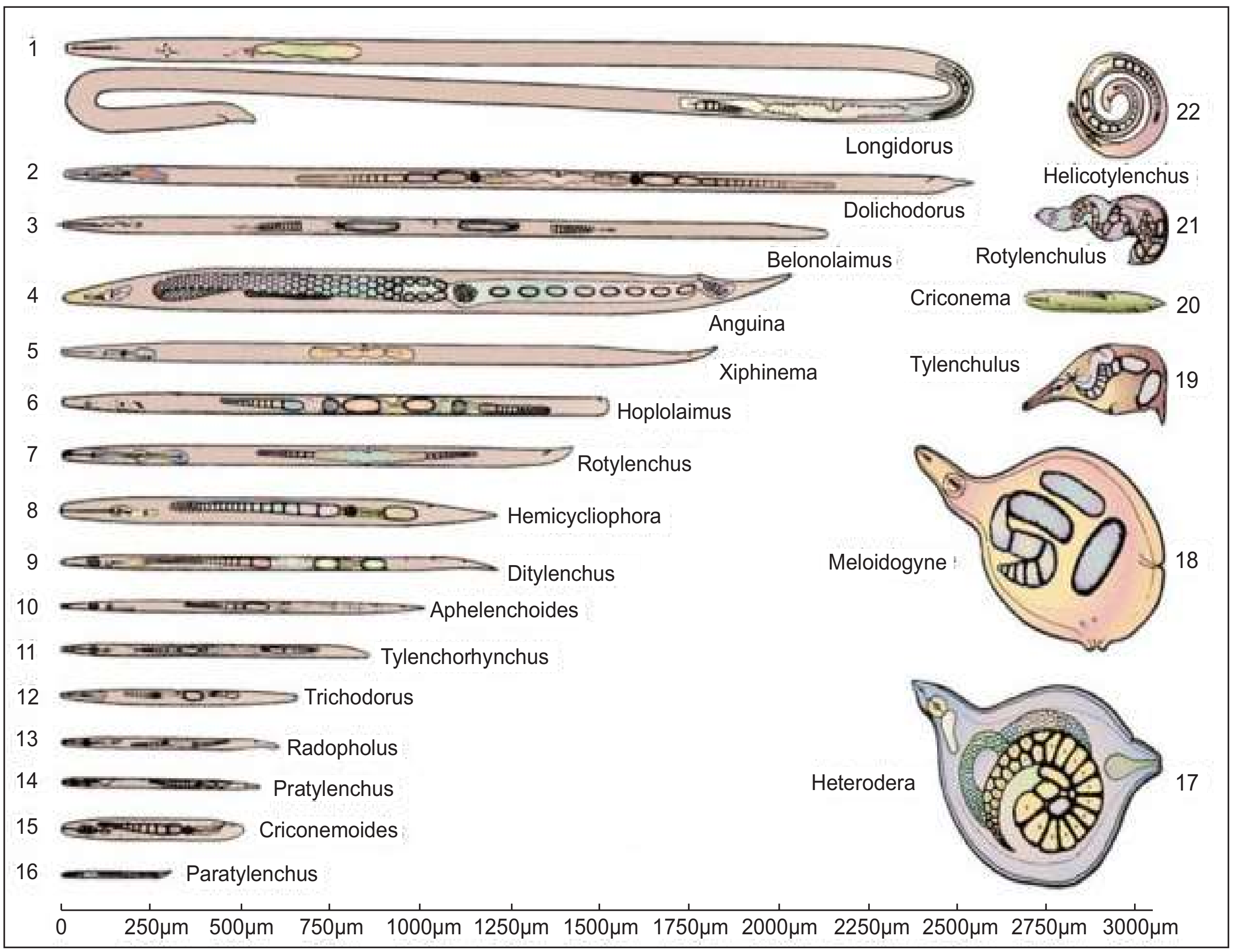

Figure 1: Major general of plant parasitic nematodes and relative size[17]

NATURE OF DAMAGE

Plant-parasitic nematodes are obligate parasites and they feed cytoplasm plant cells. Nematodes feed ectoparasitically on root hairs/epidermal cells and some are fed as sedentary or migratory endo-parasites. Phytonematodes are broadly grouped into three categories, viz. ectoparasites, semi-endoparasites and endoparasites, based on their feeding habits. Ectoparasitic nematodes are a primitive group and feed externally by inserting their stylet/spear into the cells of root hairs and root tips. They are migratory *(Tylenchorhynchus Belonolaimus, Trichodorus, Paratrichodorus.)* and frequently move over the root surface, and others are sedentary ectoparasites (*Hemicycliophora, Paratylenchus, Xiphinema, Longidorus*) feed sedentarily on deeper cells by penetrating their long stylet. Nematodes that invade the host tissues are endoparasites. Endoparasites are further grouped into migratory and sedentary. Migratory endoparasites (*Pratylenchus, Radopholus, Hirschmanniella, Bursaphelenchus*) invade roots, stems, leaves, rhizomes, and bulbs and cause extensive damage, their migration through the cortex tissues leading to the formation of cavity and lesions, while sedentary endoparasites (*Meloidogyne, Heterodera, Globodera*) are advanced parasites causing economic damage to the crops. Invasion of plant tissues by sedentary endoparasites and their oesophageal gland cell secretion through the stylet induce cellular changes to establish their feeding sites. Damage caused by nematode the symptoms appear on above and below-ground parts of plants.

1. Above-ground symptoms

Symptoms appear above ground on plants unthrifty and patchy growth, reduction of foliage, stunting, yellowing of leaves, and decline of plants,. slow decline, spreading decline, angular leaf spots and necrosis white tip, wilting of plant, reduction in several tillers, crinkling, curling and twisting malady on tuberose, grain discoloration, seed gall, stem gall, leaf gall and galls on peanut shells, blackhead, replant problems.

2. Below-ground Symptoms

Symptoms appear on below-ground parts on root form gall, swelling of the root tip, forking, branching, stubbed root and coarse root, lesions, brown/black spots and red ring, deformation of tubers, dirty root, curly tip (fish hook), dry tuber rot etc.

NEMATODES DISEASES, VIRUS TRANSMISSION AND COMPLEX DISEASES

Plant-parasitic nematodes can cause plant diseases and interact with other microorganisms (fungi, bacteria, viruses) leading to disease complexes. Phytonematodes are obligate parasite; rarely kills the plants for their survival. The nematodes attack healthy tissues, thereby infecting other organisms, and release metabolic products capable of killing host cells directly unaffected cells to invasion other pathogens into healthy host tissue without involving nematodes in the aetiology of the disease. The nematode disease complexes were reported first time on cotton wilt (*Fusarium oxysporum f.sp. vasinfectum*), severe wilt was observed in the presence of root-knot nematode.[18] Root-knot nematode (M. incognita) infection in tomato plants with Rhizoctonia solani cause complex diseases.[19] Nematode–fungus disease complexes with different fungus by different nematodes were described.[20] The plant-parasitic nematodes also influence bacterial complex disease. Bacteria easily enter plants through wounds created by the nematode. Nematodes also transmit bacterial propagules externally on their body surface and internally within the gut. A report showed the first time tomato plants that readily attached by Pseudomonas solanacearum in nematode-infested soil.[21] Root-knot nematode (Meloidogyne incognita) with the Pseudomonas solanacearum bacteria in eggplants causes Wilt.[22] Cauliflower disease is caused in Strawberries by Aphelenchoides ritzemabosi/A. fragariae with bacteria Corynebacterium fascians.[23] Tundu disease of wheat is caused by seed gall nematode Anguina tritici with Corynebacterium michiganense pv. tritici.[24] Nematode as a vector of plant viruses is now well documented. Plant-parasitic nematodes consume the virus particles during feeding on plants, but successful virus transmission occurs by the nematode species belonging to Order Dorylaimida (*Xiphinema, Longidorus, Trichodorus* and *Paratrichodorus* spp. *Xiphinema index* successfully transmits the grapevine fanleaf virus in the vineyards in California.[25] Viruses of plants transmitted by nematodes are generally grouped as below:

1. NEPO Viruses: Nematode transmits virus of particles 25–30 nm in size, polyhedral in shape transmitted by Xiphinema and Longidorus spp. The viruses belonging to this group are grapevine fanleaf virus (*Xiphinema index)*, tomato ringspot virus (*Xiphinema americanum*) and raspberry ringspot (*Longidorus elongatus*).

2. TOBRA/NETU Viruses: Nematode transmit virus of particles 180–210 nm and 45–115 nm in size depending on isolates and rod-shaped transmitted by Trichodorus and *Paratrichodorus* spp. The viruses belonging to pea early browning virus (*Paratrichodorus anemones*), pepper rings pot virus (*Paralongidorus maximus*), tobacco rattle (*Trichodorus similis*), A list of diseases caused by nematode and complex diseases are given in Table 2.

Table 2: 3 Important diseases caused by phytonematodes

Sl No.	Diseases and complex diseases	Cause of nematodes
1	Root-knot diseases	*Meloidogyne incognita, M. javanica, M. areneria, M. hapla*
2	Peach replant problem	*Pratylenchus penetrans*
3	Spreading decline of citrus	*Radopholus citrophilus*
4	Banana decline, black head, Rhizome rot	*Radopholus similis*
5	Pepper yellow	*Radopholus similis*
6	Kork disease of barley	*Anguina radicicola*
7	Eracockle/sehun/mamni/gegla of wheat	*Anguina tritici*
8	'Tundu' yellow ear rot of wheat	*Anguina tritici* +*Clavibacter tritici*
9	Gumming diseases of rayegrass	*Anguina funesta* + *Rathayibacter toxicus*
10	Red ring disease of coconut	*Phadinaphelenchus cocophilus*
11	Dry rot of yam	*Scutellonema bradys*
12	'Kalahasti' diseases of groundnut	*Tylenchorhynchus brevilineatus*
13	Slow decline/dieback of citrus	*Tylenchulus semipenetrans*
14	'Mentek' of rice	*Hirschmaniiella oryzae*
15	'Molya' disease of wheat and barley	*Heterodera avenae*
16	Tuber dry rot of potato	*Ditylenchus destructor*
17	Ufra diseases of rice	*Ditylenchus angustus*
18	'Cauliflower' diseases of Strawberry	*Aphelenchoides ritzemabosi* + *Clavibacter fascians* *Aphelenchoides fragariae* + *Clavibacter fascians*
19	Blind plant/crimp/spring dwarf of strawberry	*Aphelenchoides fragariae*
20	Summer dwarf of strawberry	*Aphelenchoides besseyi*
21	Firefly blast/white tip of rice	*Aphelenchoides besseyi*

ECONOMIC IMPORTANT NEMATODES

Economically important plant-parasitic nematodes of different crops in India have been documented.[26] Some important genera of nematodes are described as follows.

1. *Meloidogyne* spp. (Root-knot Nematode)

Root-knot nematodes obligate parasites and are widely distributed in several countries of the world with many plant species of roots, including monocotyledonous and dicotyledonous, herbaceous, and woody plants in annual, biennial, and perennial plants.[27] Root-knot nematodes are obligate plant parasites and are widely distributed in many countries of the world. Root-knot nematodes occur mainly in tropics, subtropics, and warmer regions of the world.[28] Root-knot nematodes are roundworm plant-parasitic.[29] The important four major species are the tropical *M. arenaria*, *M. incognita* and *M. javanica*, and the temperate *M. hapla*.[30] *M. arenaria, M. hapla, M. incognita*, and *M. javanica* are made up of 99% of all species.[31] *M. incognita* is widely distributed in Asian, African, European, Oceania, and American countries.[32] Disease complexes with Fusarium wilt, Rhizoctonia solani and Thielaviopsis basicola, have also been reported.[33] The most economically important plant-parasitic nematode species is M. incognita damaging horticultural and field crops and widely spread in tropical and subtropical continents of the world.[32] Root-knot nematodes are the most destructive and cause yield losses, in quality, and quantity.[34,35,36] The population densities increased in sandy soils than in silt and clay[37,38] Root-knot nematode is a polyphagous endoparasite of plants that causes serious problems for the growing plants.[39] It spread a short distance by water and wind and in the new geographical area through contaminated planting material. Long-distance spread by the contaminated soil, rootstocks, and planting materials. The symptoms occurred both above and below the ground part of plants. The above-ground symptoms, stunted growth, yellowing of leaves, leaf chlorosis, plant death, wilting of leaves, and poor shoot growth.[40] The below-ground symptoms are galls on primary and secondary roots; galls are varied in size and can be reached up to 15 mm in diameter.[41] Globally, the annual yield loss of crops caused by Meloidogyne species is estimated to be $157 billion.[42]

2. *Hetereodera* spp. (Cyst Nematode)

Cysts, the resting structure, contain the eggs resulting from the dead female body and persist in soil for several years. The cyst nematodes survive prolonged periods in the soil in the absence of a host.[43] A cyst is the dormant stage of the life cycle and host-specific species, hatching occurs in response to a host-derived chemical from root diffusates.[44] *Heterodera avenae causal* organism of disease and is popularly known as molya of wheat and barley, 11 biotypes of *H. avenae* are known worldwide. In India, the occurrence of five biotypes from Rajasthan and Haryana.[45] It's caused molya disease as recorded for the first time from the Sikar district of Rajasthan in India[46] and subsequently, occur in wheat-growing states.[47,48] Infested fields appear with patchy growth with stunted and yellowish plants, narrow leaves, reduced tillering, and small size of ear heads with a reduced number of grains often confused with nutrient deficiency symptoms. The roots of plants appear bushy and bunchy due to the emergence of rootlets at the site of infection, and slight swelling of the root tips. The second-stage juveniles (J2) infect the growing tips of roots and develop specialized feeding sites of syncytial cells in the stele. Later the juveniles attain lemon-shaped cyst which is found to attach to roots. Eggs are laid inside the female body, and the death of the female body cuticle transforms into a brown cyst. The length of the life cycle of the cyst nematode is depends on the temperature. Pigeon pea cyst nematode (*Heterodera cajani*) parasitizes a large number of leguminous crop, the first time reported on pigeon pea from India.[49] Crops like pigeon pea, cowpea, mungbean, moth bean, cluster bean, garden pea, soybean, black gram and sesame are damaged by the cyst nematode.

3. *Rodopholus similis* (Burrowing Nematode)

The nematode is a migratory endoparasite of the root that feeds succulent tissues of feeder roots. The intracellular movement of the nematode forms a burrows/cavity inside the root. All the developmental stages are feeding the roots. Eggs are laid in root tissues and hatched juveniles start feeding inside the roots. *Radopholus similis,* is the only pathogen of widespread and economically importance.[50] Rodopholus similis is an endo-parasitic nematode in nature, occurring in a wide host range and under internationally quarantined pests capable of parasitizing many fruits, spices and plantation crops. It is responsible to cause the disease of black pepper as 'pepper yellows' in Indonesia, 'slow wilt' in India and 'spreading decline' in Florida. It is known to be a destructive pest of economically important crops like banana, citrus, betel vine, coconut, areca nut, black pepper, and ginger, which are seriously affected by the nematode. In India, the problem is in southern states viz., Kerala, Karnataka and Andhra Pradesh.[51] Infested banana plants show toppling disease at the bearing stage, premature defoliation, poor plant vigour and reduction in bunch size and weight. On roots develops lesions and subsequent rotting and decaying of roots due to the involvement of other soil microorganisms. Tissue rot occurs as a result of secondary bacterial/fungal infections.[50]

In black pepper, vines yellowing of leaves, panicle declines followed by dieback and death of vines. Coconut plants show general "decline" symptoms viz., yellowing, stunting, decrease in leaf size and button shedding. The coffee, areca nut and betel vine roots have characteristic lesions on roots, decay and rotting.

4. *Pratylenchus* spp. (Lesion nematodes)

Pratylenchus are known worldwide and wide host range. Economic importance crops attacked by the nematode viz.; wheat, maize, cotton, potato, rice, coffee, banana, tea, vegetables, ornamentals and fruits. Pratylenchus spp. are economically pests of many crops, such as cereals, causing yield losses of up to 30% in wheat in Australia[52] infect other crops, such as sugarcane, coffee, banana, maize, legumes, potato, many vegetables and fruit trees.[53] Lesion nematodes (*Pratylenchus* spp.) are migratory endoparasites of the root. The name 'root lesion' is derived from the necrotic discoloured patches (lesions) that develop on roots. The most important species are *P. penetrans*, *P. thornei*, *P. neglectus*, *P. zeae*, *P. vulnus* and *P. coffeae*. *Pratylenchus* spp. are polyphagous. Pratylenchus thornei in wheat, soybean, chickpea, sunflower and opium, *P. zeae* in maize, *P. indicusin rice*, *P. loosi* in tea.[54] *P. coffeae* in coffee and banana and *P. pratensis* and *P. vulnus* in fruits are serious problems. All the stages of this nematode are infective. The infected plant's root shows dark red-brown lesions are the most characteristic symptom, initially appearing as small, elongated, water-soaked spots and later turning brown to black. The interaction of *P. penetrans* and *Verticillium* wilt fungi induce a disease complex, known as 'potato early dying syndrome', which leads to premature vine death and severe yield losses. Infects potato tubers causes a scabby appearance with sunken lesions, and wart-like bumps that turn purple on tubers in storage.[55]

5. *Tylenculus semipenitrans* (Citrus nematode)

The citrus nematode is found in all the citrus-growing areas of the country and is a widely recognized and economically important pest of citrus. The slow decline in citrus is one of the causal factors that is characterized by a reduction in tree growth, lack of vigour, yellowing of foliage and small size of fruits. The citrus nematode was first discovered infecting citrus in California, identified as new species, *Tylenchulus semipenetrans*, as the causal agent of a slow decline in citrus.[56] *Tylenchulus semipenetrans* have been found in every citrus-growing region of the world.[57] Nematode of the feeds surface layers of roots causing discolouration and necrosis. The posterior part of the mature female body remains outside and eggs are laid in a gelatinous matrix outside the host tissue. *Tylenchulus semipenetrans* is a semi-endoparasite nematode of the citrus root. A young female of citrus nematode penetrates the deeper root tissues and establishes a feeding site around the head. The feeding site comprising 16 cortical cells is referred to as a 'nurse cell'. The citrus nematode is often unseen in the seedlings stage in the nursery which causes extensive distribution. The symptoms causes often non-descriptive and difficult to diagnose. The female nematodes produce gelatinous matrix-containing eggs that adhere to soil particles and give a dirty appearance to the roots which is not easily washed off. The most serious effects of the nematode of citrus are usually encountered when new seedlings are planted in the old orchard, this condition is known as the 'citrus replant problem'. This slow decline infested trees and general deterioration of citrus trees beginning with the production of smaller and fewer fruits.

6. *Rotylenchulus reniformis* (Reniform Nematode)

Rotylenchulus reniformis, is a sedentary semi-endoparasite of a large number of annual and perennial plant species. The reniform nematode, the name given due to adult female kidney-shaped, nematode obligate and sedentary semi-endoparasite. R. reniformis is the most prevalent species and attacks over 150 plant species of different families.[58] The first report of R. reniformis feeding on cowpea. About 10 species of Rotylenchulus are known to survive over the world.[59] This nematode is now known to occur in almost all states of India.[60,61,62] In India, tomato, brinjal, onion, and pointed gourd, has been reported as hosts for this nematode.[63] There are two races/biotypes that occur as race A and race B in R. reniformis, Race A completes its life cycle on cowpea, castor and cotton race B on cowpea only.[64] Occurrence of four physiological races based upon the reproduction capabilities of cotton, pearl millet, cowpea, castor and mustard as reported.[65] *R. reniformis* is a major pest in the southern USA, widespread in tropical and subtropical regions. The wide host range of economically important vegetables, fruits, ornamentals and fibre crops, as well as weeds.[66,67] *R. reniformis* interacts with other pathogens like *Fusarium* spp., *Verticillium* spp., *Sclerotium rolfsii* and *Rhizoctonia solani* leading to disease complexes. Young females, males and fourth-stage juveniles survive in a coiled anhydrobiotic state within in soil.

7. *Hirschmanniella* spp (Rice-root nematode)

Rice root nematode (*Hirschmanniella* spp.), is a migratory endoparasite of roots, and predominantly in rice soil, causes yield losses of 19 % in rice.[68] *Hirschmanniella oryzae* and *H. mucronata*, are economically important and widely distributed in the rice-growing area. The juveniles and adults penetrate roots and feed on cortical cells, leading to the formation of cavities in the roots, infected plants disrupted and plant growth reduced. The aboveground symptoms are stunted growth, leaf chlorosis, reduced tillering and delayed flowering. The population build-up of this nematode in the transplanting of rice.[69] Weeds in rice fields serve as an alternative host for this nematode.

8. *Ditylenchus* spp (Stem and bulb nematode)

The potato rot nematode is caused by *D. destructor*, and peanut pod nematode, (*D. africanus*. *D. myceliophagus*) and commercial mushroom *(Agaricus bisporus)*. *Ditylenchus dipsaci* is a migratory endoparasite commonly known as 'stem and bulb' nematode, and distributed worldwide, especially in temperate regions. It is one of the quarantine organisms of many countries that infects onion and garlic.

D. dipsaci enters plants through stoma or wounds, releasing enzymes that soften cell walls and facilitate feeding on the parenchymatous cells of the cortex, all stages are infective. *Ditylenchus dipsaci* and *D. gigas* are nematodes that survive desiccation in a dormant state. The fourth-stage juvenile (J4), desiccate coil and clump together in masses termed 'eelworm wool', usually around the basal scales of bulbs *(D. dipsaci)* and inside bean pods *(D. gigas)*, where they can overwinter. J4s can survive more than 20 years in a dry state. Ditylenchus angustus, causes rice disease and is called Ufra, feed ectoparasitically on meristematic tissues of stems, and leaves in deep-water and lowland rice. Symptoms appear in patches initially and spread the entire field. The nematode cause diseases swollen ufra that panicle does not come out; it remains enclosed within the leaf sheath and infected portion tending to branch. Ripe ufra panicle emerges partially and bears filled grains at the tip only. The common symptom appears as twisting of leaf and leaf sheath. The nematode overwinters through the quiescent state (J4 stage) which remains viable for up to 15 months. They live in a coiled anhydrobiotic state in grains.[70]

9. *Aphelenchoids* spp. (Leaf and bud nematode)

The nematode *Aphelenchoides besseyi* attacks aerial parts of the host, rice. It can infect tuberose, onion, soybean, sugar cane, oat, millets, and orchids, active in above-ground plant parts under moist conditions. The foliar nematode *A. besseyi* is causing severe damage to tuberose in Hawaii,[71] West Bengal[72,73,] Orissa of India[74,75] and Mekong Delta of Vietnam.[76] *A. besseyi* causing 'white tip disease' in rice is the same population infecting tuberose and causing floral disease.[77] The nematode survives in quiescent pre-adult and adult stages in the scaly leaves outside the bulbs. *Aphelenchoides besseyi* primarily disseminates through infested bulbs, dry plant parts and runoff and irrigation water from one field to other fields. Aphelenchoides besseyi is an important pathogen that causes 'white tip' disease on rice, with an estimated $US16 billion damage caused by nematodes to rice crops.[78] The disease is seed-borne, and infected plants are reduced in size. *A. besseyi* survives in pre-adult and adult stages (quiescent state) beneath the hull of the rice kernel. *A. besseyi* spread infected rice seeds through irrigation water. The disease symptom is 'white tip' in rice leaf produced by this nematode, hence the common name of the nematode, 'white tip nematode'. The tip of the flag leaf is often twisted, which emergence of panicles. On average, yield losses are 10–60%. These foliar nematodes feed as ecto and endoparasites on above-ground plant parts, their ability to feed on fungi to survive in the absence of a plant host. The common name of Aphelenchoides ritzemabosi is chrysanthemum foliar nematodes. Chrysanthemum plant usually exhibits elongated to angular spots. The development of disease symptoms and disease severity on chrysanthemum depends on host varieties and nematode races.[79] Several ornamental plants like *Zinnia elegans.*[80] *Z. elegans* numerous small rectangular spots, spots of triangular to pentagonal shapes also appear. Zinnia plants more damage as compared to chrysanthemum and its depending upon the environmental conditions. The strawberry foliar nematode is *A. fragariae* predominantly plant parasites.

10. *Anguina tritici* (Seed gall nematode)

Seed gall nematode is the first plant-parasitic nematode as described in the scientific literature in 1743. The Seed gall nematode is one of the most serious pests of wheat, causes ear-cockle disease in wheat, and in association with the bacterium *Clavibacter tritici,* it produces yellow ear rot or tundu disease. Symptoms appear as twisting curling and crinkling of leaves and stunted growth in the early stage of plant growth. The survival stage is the second-stage juvenile (J_2) of *A. tritici* and is viable in an anhydrobiotic state inside the cockle for up to 30 years. A large number of second-stage juvenile (J_2) are released from seed galls after sowing as come in contact with soil moisture. These J_2s infect the growing point of seedlings as an ectoparasite, causing leaf distortions, as reach the inflorescence, enter the floral primordia and become endoparasite, and floral primordia convert into seed gall (cockle).

11. Ecto-parasitic nematodes

Ectoparasitic nematodes genera are *Tylenchorhynchus, Hoplolaimus, Helicotylenchus, Paratylenchus, Hemicriconemoides, Hemicycliophora, Criconemoides, Xiphinema, Longidorus, Trichodorus* are prevalent in the rhizosphere of agricultural, horticultural and forest crops. Ectoparasitic nematodes are given the least attention because plants are often confused with soil problems and soil pathogens. The nematodes are more dangerous when they interact with other soil microorganisms. Tylenchorhynchus brevilineatus is a polyphagy ectoparasite of various crops, as a serious problem disease of Kalahasti malady on groundnut in Andhra Pradesh and cause 20–60% yield losses.[81] *Hoplolaimus indicus* effect in rice and jute crops, *Helicotylenchus multicinctus* in banana, *Paratylenchus* and *Criconemoides* in apple and peach, *Xiphinema basiri* and *Hemicriconemoidesin citrus* and grape and Paralongidorus in sal are emerging as nematode problems.[82] *Xiphinema index* is a significant parasite of grapevine as a worldwide distribution.[83] Its economically important host crops are grapevine and fig and are associated with rice feeding ectoparasitically on root tips.[84] Feeding activity causes gall formation and reduces the growth of infected plants. Cells within the gall tissue are enlarged and multinucleated.[85] *X. index* is a vector of *Grapevine fanleaf virus* (GFLV)[25] and one of the most important viruses of grapevine.[86] In the nematodes, cuticular lining, the lumen of odontophore and pharynx, plant virus particles are attached. The virus can be retained for up to 4 years.[87]

6. Integrated nematode management (INM)

Management of plant-parasitic nematodes is difficult in a soil environment.[88] Cultural methods, chemical, biological and use of plant resistance have decreased the risk of many nematode species.[89-93] Chemical pesticides can have negative effects on the environment and human health.[94,95] Plant-parasitic nematode infestations with multiple nematode species can complicate management strategies. Integrated methods for the management of plant-parasitic nematodes have been proposed for high and low-value crops.[96,97] An integrated management strategy requires in the cropping system. The cropping sequence must be designed as an integrated management system to reduce the population densities of nematodes. IPM is divided into several components such as biological monitoring, environmental monitoring, decision-making, the decision-support system, the decision, procedure implementation, and the system.

M. incognita can reduce the severity and intensity by cultural practices viz., crop rotation, fallowing, flooding, sanitation, ploughing 2–3 times, mulching, adding up organic manure, planting space, time of sowing, and cover crops.[29,98] A fallow method is very effective in warm climates.[99] The application of the decomposed leaves *(Tagetes erecta)* to the soil reduces the numbers of J_2 in the soil, the number of root galls, and egg masses.[100] Chicken manure is very effective in reducing *M. incognita* egg masses by 56%. The poultry manure can significantly reduce both the number of root galling and nematode populations. Organic matter in the soil also suppresses the number and diversity of plant-parasitic nematodes in soil.[101] The crop residues of broccoli *(Brassica oleracea)* with Trichoderma inoculants could decrease the *M. incognita* population.[102] The trap crops and antagonistic crops, Mexican marigold *(Tagetes erecta)* and rattlebox *(Crotalaria spectabilis)* in nematode-infested soil are effective against the root-knot nematode. Marigold, chrysanthemum, castor bean, partridge pea, velvet bean, vetch, rapeseed, and sesame have also the capability to suppress nematode populations in the soil.[103] The intercropping of sesame with okra by distancing 15–30 cm reduces the intensity.[104] Five-year rotation with a non-host crop is recommended.[105] The combined application of poultry manure at a rate of 5 to 15 t/ha and rapeseed cake at 200 kg/ha on tomato reduces the number of M. incognita J2 stage, egg mass, and root galling index by improving the fruit yield.[106]

Biological control has a minimal detrimental environmental impact and it is currently accepted as a practice in sustainable agriculture. There are several predators, parasites, nematophagous fungi, endoparasitic fungi, predacious fungi, and opportunistic fungi which more or less minimize nematode control. *P. fluorescens, Bacillus subtilis,* are important in nematode control. The bacteria are easy to culture in vitro and they produce toxins against nematodes they induce suppressive activities against *M. incognita* by minimizing gall formation, controlling nematode reproduction, and hatching and killing juveniles through the release of toxins.[107-110] The fungal biocontrol agent *Paecilomyces lilacinus* is an egg parasitic on *M. incognita* and reduces the egg masses by 50%. Trichoderma penetrates the nematode egg mass matrix and decreases its hatching.[111] Toxic metabolites directly inhibit nematode penetration and development.[112] *T. harzianum* has a greater toxicity level against *M. incognita* than *T. viride*.[113] Pasteuria penetrans are used for the knockdown of J_2 infestation.[114,115,116] Bio-agents Paecilomyces lilacinus and Pasteuria penetrans were considered good management practices of *M. incognita* and *utilizing* both was considered a good control method. The integration of Pacecilomyces lilacinus bio-formulations with farmyard manure (FYM) and neem cake was the most effective in reducing root galling.[117] The integration of neem with fungal biocontrol agents *(Paecilomyces lilacinus and Verticillium lecanii)* could reduce the *M. incognita.*[118] *Pseudomonas* spp. acts as a biopesticide, generally present roots of different plants, *Pseudomonas fluorescens* produced toxin protein product to kill nematodes.[119] Bacteria *Pseudomonas fluorescens* produce bacteriocin and have a role in reducing nematode population, gall formation in tomato plants and enhancing crop yield.

The aqueous extracts of holy basil *(Ocimum sanctum)* have high potential against *M. incognita* (J_2 hatching) as compared to neem *(Azadirachta indica)*, papaya *(Carica papaya)*, ricinus *(Ricinus communis)*, French marigold (Tagetes patula), and untreated control.[120] *A. indica* and carry leaf *(Murrage koenigi)* show the best performance in reducing the number of *M. incognita.*[121] Chemicals in root exudates can attract/repel nematodes via motility inhibition.[122] The nematicide extracted from tobacco *(Nicotiana tabacum)*, clove *(Syzygium aromaticum)*, betel vine *(Piper betle)*, and sweet flag *(Acorus calamus)* were effective in killing the nematodes under laboratory condition.[123] Leaves extracts at 5% concentration of mexican marigold *(T. erecta)*, bitter *(Vernonia amygdalina)*, lantana *(Lantana camara)*, and seeds of baker tree *(Cupressus bakeri)* were most effective *(> 95% hatching inhibition)* against the juveniles hatching in the laboratory.[124] Neem leaf, neem oil, and neem cake use to control plant-parasitic nematodes.[125] Plant extracts such as thiophenics, alkaloids, glucosides, phenolics, and fatty acids are helpful in nematode control as they are generally safe for the environment and human health.[126,127] Plant-parasitic nematodes have mainly been controlled by nematicides and chemical soil fumigants for decades but in recent years, several nematicides have been withdrawn from the market because they cause environmental pollution.[4] Nematicides were very effective against nematodes such as Nemagon, Mocap, Dasanit, Nemacur, Furadan, Temik, and Vydate. Non-fumigant nematicides were applied into the soil pre and post-planting for suppression of root-knot nematode.[104] Soil fumigants are more effective than non-fumigants for managing root-knot nematode in Florida.[128] Fumigants should apply at least 3 weeks before planting because they cause phytotoxic to plants. The fumigant chemical such as Metam-sodium (Vapam), 1,3-dichloropropene (Telone).[129,104] Synthetic pesticides alone is highly harmful to man and the environment. Therefore, suggested that the utilization of nematicides with organic amendments as animal wastes and other management practices is better in an integrated form.[130] Biocontrol agents such as *P. lilacinus* and *Trichoderma viride* alone or in combination with mustard oil cake and nematicide of carbofuran group promoted the plant growth and ability to suppress the number of galls and egg masses of *M. incognita.*[131] Several environmental problems regarding the use of chemical nematicides for control of plant-parasitic nematodes, and the use of plant essential oils as natural products in pests management systems.[132] These plants essential oils can be used as alternatives in plant nematode management.

CONCLUSION

The economically important plant-parasitic nematodes are damaging horticultural and field crops. Phytonematodes are obligate parasites of thousands of plant species of monocotyledonous and dicotyledonous and can attack the annual, biennial, and perennial plants species belonging to different families. Nematodes can identify by morphological, biochemical, molecular, real-time PCR, and loop-mediated isothermal amplification (LAMP). Plant-parasitic nematodes are causing huge yield losses in crops. The damage caused by the nematode crop losses is estimated at $100 billion per annum. *Meloidogyne incognita* is the primary pathogen that causes complex diseases with secondary pathogens like bacteria, fungi, and viruses. Nematode problems can be managed by cultural, biological, using resistance varieties, botanical extracts, chemical, and their integration. Management of nematodes through chemicals is not economically viable and also environmental hazardous. The management benefits greatly from the use of alternative control methods in IPM strategies. Bio-intensive approaches help long-lasting management of phytonematodes and it is also economically viable. Economically important pests should aware to farmers for making management in sustainable agricultural crop production and also small-scale farmers in the future.

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