PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 12(2): 1-9
https://doi.org/10.14719/pst.6862

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REVIEW ARTICLE

Management of nematode menace in protected cultivation of vegetables in India

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OPEN ACCESS

ARTICLE HISTORY
Received: 22 December 2024
Accepted: 02 April 2025
Available online
Version 1.0 : 24 April 2025
Version 2.0 : 30 April 2025

Check for updates

Additional information
Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
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CITE THIS ARTICLE
Senthil PK, Pragadeesh ARU, Sandhya N, Abishagu A, Kumar MS. Management of nematode menace in protected cultivation of vegetables in India. Plant Science Today. 2025; 12(2): 1-9. https://doi.org/10.14719/pst.6862

Abstract

The adoption of protected cultivation techniques has significantly enhanced vegetable productivity in India, by offering numerous advantages such as extended growing seasons, increased yield and better control over environmental conditions. Growing crops under protected cultivation has multi-faceted benefits; however, the adoption of sequential cropping pattern in these closed structures has led to the prevalence of soil borne pathogens, nematodes and pest incidence, which became a major hindrance to the sustainable agriculture. Continuous cultivation of crops without adequate rotation or sanitation measures in the same soil creates a conducive environment for pest and disease proliferation. Prevalence of nematode infestation is particularly concerning as they pose a serious threat to the yield and quality of agriculture production. Nematodes, such as root-knot nematodes and reniform nematodes, can survive in the congenial conditions of higher temperatures and humidity present in the protected cultivation structures. Nematode infestations can cause significant damage to the root systems of plants, leading to reduced water and nutrient uptake, stunted growth and lower yields and symptoms like chlorosis, wilting and stunting will appear after the significant damage. This review discusses the key nematode species affecting crops under protected cultivation, their impact on crop health and productivity, their ecological interactions and various integrated management strategies. Integrated management strategies, including biological, chemical and cultural practices, are essential for mitigating the menace caused by the plant parasitic nematodes. Cultural practices such as crop rotation and soil solarisation, chemical treatments with nematicides, Biological control using biocontrol agents and natural predators, are all part of a comprehensive strategy to manage nematode populations effectively and sustain the productivity of protected cultivation systems.

Keywords

management; nematode; plant parasitic nematode; protected cultivation; vegetables

Introduction

Growing of crops under protected cultivation has become an integral component in off-season production and especially in cultivation of high-value vegetables in India (1). Protected cultivation structures includes greenhouses, polyhouses and shade nets that can offer protection against abiotic stresses like extreme wind, temperature and rainfall and creates a favourable conditions for plant growth (2). Over the past decade, India has witnessed a constant increase in area under protected cultivation. As of 2022, more than 50000 hectares are under protected cultivation (Horticultural Statistics, Government of India, 2022).

About 10 % countries' vegetable productions comes from the protected cultivation. Crops such as tomato, capsicum, cucumber and lettuce have benefited immensely, with yield increases of up to 200 % compared to open field cultivation (NHB, 2021). Through domestic and export markets protected cultivation contributes significantly to the economy, generating approximately INR 15000 crores annually (3). Despite these benefits, ecological conditions created in polyhouses favours pest and disease incidence, which are not often encountered in open-field conditions (4). Among the various soil-borne pests, plant parasitic nematodes became a major limiting factor in protected cultivation of vegetables.

Nematodes are worm-like microscopic animals, as they possess several animal systems other than skeletal, respiratory and circulatory system; they are not true micro-organisms. They are aquatic in nature, except air they inhabit rivers, lakes, oceans and in soil water. Earthworms are not to be confused with nematodes, as they are macroscopic and beneficial in nature. Plant-parasitic nematodes are a group of unsegmented worms' predominantly affecting root systems and microscopic in nature. Globally, they cause 10-15 % of annual yield losses, valued over $125 billion approximately. In India, plant-parasitic nematodes account for 10 % to 40 % yield loss in vegetables, valued over INR 1200 crores approximately (5). The microclimate of protected structures, stable warm and humid conditions became ideal for nematode proliferation. Improper cultivation practices like continuous cropping, absence of natural predators, high density planting promotes the nematode infestations. Improper management and failure to address this menace not only have direct consequences in yield but also reduces the profitability of protected cultivation. Nearly 70 % of farmers rely on chemical nematicides, which contribute to 15% of the total input costs in protected cultivation systems (6). Heavy reliance on chemical control methods, such as use of nematicides and fumigations has a detrimental effect on environment through soil contamination, groundwater pollution and other human health hazards (7).

The major nematode species affecting protected cultivation include *Meloidogyne* spp. (root-knot nematodes), *Rotylenchulus* spp. (reniform nematodes), *Pratylenchus* spp. lesion nematodes (8). These plant-parasitic nematodes (PPNs) are often considered as hidden enemy as they are subterranean in habitat and farmers are unaware of the infections caused by them. Many nematode damages were unreported or often considered as fungal attack, physiological disorder or moisture stress. Late diagnosis leads to severe yield loss. Both endo & ectoparasitic plant-parasitic nematodes dwell in soil and feed on plant roots and other underground parts like rhizomes, tubers, suckers and bulb (9). Thousands of PPNs feed continuously on the roots, withdraws plant nutrients and water. It adversely affects the absorption of water and nutrients by the roots from soil and their translocation to shoots. As plant-parasitic nematodes are obligate parasites, to ensure their own survival, they rarely kill their host (10). Due to poor supply of nutrients, the plants became weak, stunted and pale in colour. Moreover, they often predispose secondary infections in plants through pathogenic fungi and bacteria leading to high plant mortality (11).

Among the plant-parasitic nematodes, *Meloidogyne incognita,* accounts for nearly 60 % yield loss in protected cultivation. They affect the root integrity; obstruct water and nutrient uptake, causes secondary infections. In tomato, root-knot nematodes can cause yield losses of 20-60 %, while in cucumber, the losses range between 25 % and 80 %, depending on infestation severity (12). Rapid spread of nematode infestation through soil, crop residues and indiscriminate use of agro chemicals in horticultural ecosystems is a major concern for crop protection. Understanding the ecology and biological behaviour of nematodes is important for developing sustainable and effective management strategies (13). Research advancements in precision agriculture and molecular biology offers more promising solutions for nematode management. This review aims to provide a comprehensive analysis of the nematode problem in protected vegetable cultivation in India. It highlights the biology of key nematode species, their impacts on vegetable crops and various management strategies, emphasizing sustainable and environmentally friendly approaches.

1. *Diversity of nematodes: Ecological roles, adaptations*

Nematodes inhabit a broad range of diverse environments, often outnumbering other animals in species counts with estimates suggesting 25000 to over 1 million species. Nematodes inhabiting soil can be classified into two major groups' free living and plant-parasitic nematodes. Free living nematodes present in all type of soils, they are mostly microbial feeders, predators or saprophytic (14). Recent research advancement demonstrated the ability of entomopathogenic nematodes that have significant role in integrated pest management. Free living nematodes also play an important role in nutrient recycling by organic matter decomposition and soil health. However, plant parasitic nematode dominates in soils with vegetation. Plant parasitic nematodes (PPNs) are thread – like vermiform in structure, 0.5 to 2.0 mm in length and possess a hollow, needle like structure stylet as mouth part, that can able to suck nutrients and water from host (15). Plant parasitic nematodes are obligate parasities, can survive only on plant system, hence they feed on all kinds of plants from trees to grasses and can survive in all type of climatic conditions wherever vegetation is there (10). This ability of plant parasitic nematodes to adapt to different environmental conditions allows them to infect various crops, causing significant yield losses and became a persistent problem in sustainable agriculture. Plant parasitic nematodes can be further classified into ectoparasities and endoparasities. Endoparasites penetrate the plant tissues and feed internally. However, ectoparasites instead of penetrating plant tissues, they remain in soil and feed on roots from outside. Migratory endoparasitic nematodes are capable of moving within the tissues while other endoparasitic nematodes that remain fixed after penetration are called sedentary endoparasities. However, sedentary endoparasitic nematodes are particularly harmful due to their ability to invade and establish feeding site within the xylem and phloem cells. These nematodes can alter plant structures for their own survival, affecting the nutrient and water flow throughout the plants (16). This disruption of water and nutrient flow weakens the plant and may exhibit symptoms like yellowing leaves, wilting and stunted growth. This damage can lead to severe yield losses in agriculture. Some examples of sedentary endoparisitic nematodes are root-knot nematodes (*Meloidogyne* spp.) and cyst nematodes (*Heterodera* spp.), can siphon off essential nutrient supply through their specialized feeding sites galls and cysts. These feeding sites partially block the nutrient flow in the plant system (17).

2. Major nematode species in protected cultivation

Controlled microclimate in protected cultivation structures provides an ideal environment for nematodes to thrive. They maintain constant temperature and humidity levels that support the life cycle and reproduction of nematodes. Continuous cropping pattern and high density planting can lead to rapid population growth. Some of the key nematode species affecting protected cultivation structures are:

2.1. Root-knot nematodes (Meloidogyne spp.)

Root-knot nematodes (*Meloidogyne* spp.) comprise several species that are widespread and destructive in protected cultivation. In protected cultivation structures, on average root -knot nematodes cause 28-29 % yield losses in tomato and cucumber; and 40-70 % in disease complex situation (18). *M. incognita* and *M. javanica* are the most common nematodes world-wide, invade the plant roots and induce root gall formation. These root galls intercepts the nutrient and water flow, leading to wilting, stunted growth. They mainly infect Tomato, cucumber and capsicum, causing yield lossess upto 50 %. The life cycle of nematodes, consists of egg and four juvenile stages (J_1, J_2, J_3, J_4) and adult stage. J_2 juvenile stage is the most infective stage that causes infection in plant roots. Under favourable conditions, each female nematode can lay up to 500 eggs, leading to rapid multiplication (19).Tomato and Cucumber are the most susceptible crops to *M. incognita*. Root -knot nematodes are soil-borne; the second stage juveniles invade roots and modify the xylem and phloem into galls. After penetration into roots, they will establish parasitic feeding with plant host and becomes sedentary and swollen shape. The females start to lay eggs within in the root surface. Under optimum conditions, life cycle can be completed within a month and they can complete several generations within a cropping cycle. Initially the galls are minute and intensity and size of galls varies based on the plant host. After severe infection in plants, it will start to produce symptoms like chlorosis, stunted plant growth, wilting. Galls are different from rhizobium root nodules, nodules produced by rhizobium are beneficial in nature and with slight disturbance can be easily detached from plant roots, while galls cannot be removed (20). The infestation cycle of root-knot nematode is shown as Fig. 1.

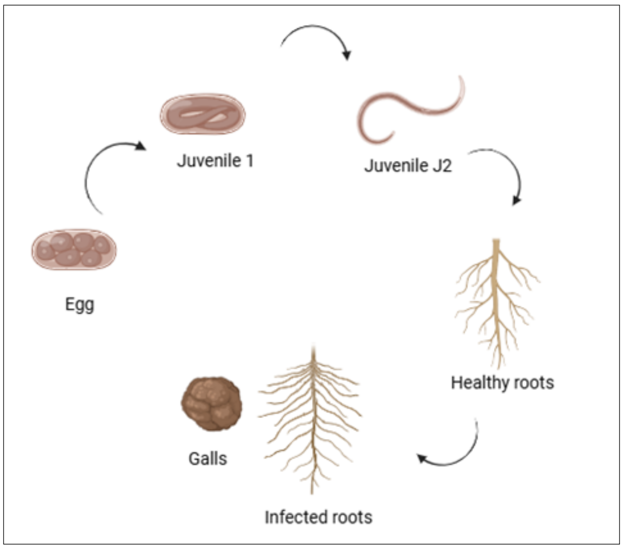

Fig. 1. Diagrammatic representation of Root-knot nematode infestation cycle. Eggs are hatched in the soil. Juvenile Stage J2 is the infective stage, penetrates the healthy roots and form root galls.

2.2. Reniform nematodes (Rotylenchulus spp.)

Reniform Nematodes are soil-borne, semi-endoparasitic nematodes, widely present in tropical and subtropical regions with warm, humid conditions (21). They are dimorphic in nature, male and females are present. Immature females are parasitic in nature, while males are non-infective in nature. Immature females penetrates anterior portion deep inside the plant stele region and establish a feeding site while the posterior position remains outside. After infection, they will form kidney shaped structures. They have short life cycle of 25-30 days and a single female can lay up to 40-50 eggs on the root surface around their bodies leading to rapid multiplication. There are around ten species in *Rotylenchulus*, *Rotylenchulus reniformis* is the most common one and causes root necrosis, yellowing and wilting (20, 21).

2.3. Lesion nematodes (Pratylenchus spp.)

Lession nematodes belongs to the genus *Pratylenchus,* they are migratory endoparasities that affect both monocot and dicot roots by creating necrotic lesions (22). They are polyphagous in nature and have wide host range, causes severe damage in apple, peach, cherry, potato, grapes. They lay eggs inside the root tissues and the emerged juveniles infect root tissues and cause root decay. They are migratory in nature; hence several generations can occur inside the roots (23). Infection of lesion nematode destroys the feeder roots and cause difficulties in replanting in orchards. Above ground symptoms include stunting, chlorosis and dieback and below ground symptoms include dark brown lesion formation on the root surface. Due to their free movement within root and plant tissues, dark lesions or spots will appear. Some species of *Pratylenchus* like *Pratylenchus neglectus, P. thornei* and *P. brachyurus* reproduce by parthenogenesis, while *Pratylenchus penetrans* reproduce by sexual reproduction. They have a life span of 45 to 65 days and can lay an average of one egg per day. These nematodes are capable of affecting all stages of plants and reduce their marketable quality (24).

3. Factors responsible for nematode menace in protected cultivation

3.1. Favorable microclimate: Stable microclimate in protected cultivation structures like optimum moisture content around the roots, ambient temperature and humidity enables the rapid multiplication of infection, as compared to open field conditions (25). Under field conditions, moisture content varies from dry to saturation whereas in protected cultivation structures, constant moisture content is maintained. Optimum temperature (15-40 °C) is necessary for nematodes multiplication. High temperatures increases the mortality of nematodes whereas low temperatures than optimum arrest the activity of nematodes. In winter season, multiplication of nematodes in open field will be arrested, whereas in protected cultivation structures, due to the optimum temperature condition they will continue to reproduce. This absence of extreme fluctuations creates a conducive environment for nematode multiplication (26).

3.2. Monocropping and high plant density: In protected cultivation, the intensive cultivation of susceptible host plants is a common practice and crop rotation with resistant non-host plants is often not practiced. The cultivation of perennial crops and growing same crops multiple times in a year, leads to a significant increase in the nematode population (27). This constant availability of susceptible host plants creates an ideal environment for nematodes to dwell and multiply. Moreover, high density planting in protected cultivation structures amplifies nematode population, as it provides a continuous host environment. The repetitive cultivation of the host crops and lack of crop rotation results in persistent life cycle of nematodes and often leads to severe infestations. Crop rotation with resistant varieties and integrated biological, chemical and cultural controls, are essential to mitigate the impact of nematodes in protected cultivation systems (28).

3.3. Limited natural predators: In the protected cultivation structures, enclosed environment restricts the activity of natural nematode predators and antagonists, such as predatory fungi, predatory nematodes and antagonistic bacteria (4). These natural enemies play a crucial role in inhibiting nematode populations in open fields by preying and competing for resources. However, in the controlled microclimate of protected cultivation structures, effect and presence of these natural enemies are reduced. This reduction in natural biological control mechanisms leads to an imbalance in the ecology, allowing nematode populations to proliferate without any hindrance. As a result, these nematodes cause severe infestations which are hard to manage. It requires integrated pest management strategies to mitigate the negative effects of nematodes on crop production. The severe nematode infestations pose a serious threat to sustainable agriculture, highlights the need for effective management strategies to ensure successful crop production in protected cultivation structures (28). Fig. 2 describes the important factors of nematode infection.

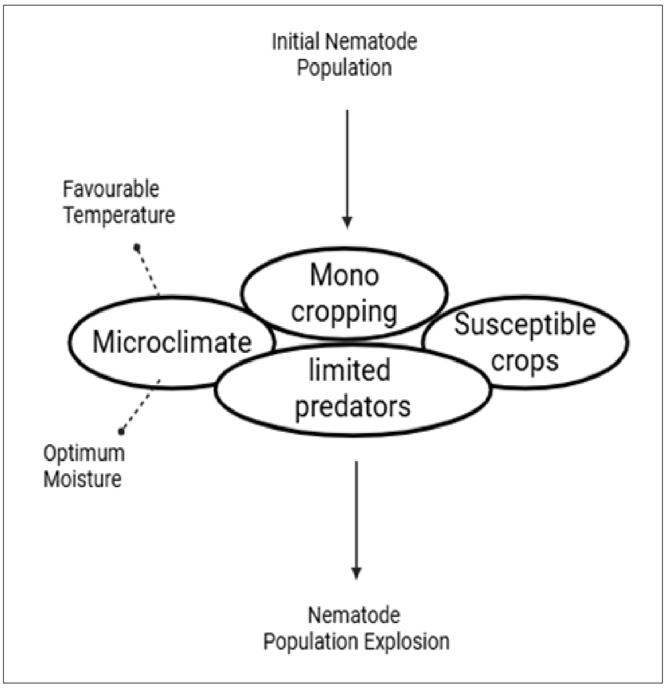

Fig. 2. Diagramatic representation of factors responsible for nematode population multiplication.

4. Impact of nematodes on vegetable crops

4.1. Direct impact: Plant-parasitic nematodes (PPNs) mainly dwell in soil and feed on plant roots and other underground structures like bulbs, tubers, rhizomes and suckers, causing mechanical damage in the root tissues and disrupts the plant nutrient and water uptake. This often results in stunted growth, wilting and chlorosis. Root-knot nematodes infections reduce the functionality of roots through gall formation, while lesion nematodes create lesions that predispose secondary infections. These Plant-parasitic nematodes feed in hundreds intermittently on the feeder roots, both ecto-parasitically or endo-parasitically within rhizosphere (8, 29). This often leads to death of affected cells and completely destroys the feeder roots. The continuous and intensive feeding of nematodes weakens the root system, results in destruction of fine rootlets and consequently diminishes the water and nutrient uptake and their translocation to shoots. As they are obligate parasites, PPNs rarely kill their host plants to ensure their own survival, instead weakens the plant and produce above ground symptoms like stunted growth, chlorosis due to inadequate nutrient management. These symptoms may be confused with nutrient deficiencies and water stress. To identify nematode-related damages, plant needs to be uprooted and inspected. This ultimately leads to qualitative and quantitative yield loss. The intensity of symptoms can be correlated with the severity of the nematode infection (30).

4.2. Indirect impact - nematode-disease complex: Beyond direct damage, Plant-parasitic nematodes (PPNs) often predispose secondary infections like pathogenic fungi and bacteria infection, leads to severe damage and plant mortality. These secondary infections are often goes unnoticed. Mechanical injuries caused by the stylets of nematodes and hydrolytic enzymes create a point of entry and favourable condition for fungal and bacterial infection. Plant-parasitic nematodes (PPNs) also transmit pathogenic microorganisms such as bacteria, fungi, virus both internally and externally. Some Plant-parasitic nematodes (PPNs) carry pathogens on their body surfaces or within their digestive systems. Lesion Nematodes (*Pratylenchus* spp.) enhance *Fusarium* infection, leads to vascular wilts and in potatoes nematodes like *Heterodera* and *Globodera* species increase the susceptibility of plants to *verticilium wilt* (31). Root-knot nematodes (*Meloidogyne* spp.) promote the infections of *Rhizoctonia solani* and *Fusarium oxysporum*, causing root rots and the galls produced by root -knot nematodes creates an ideal condition for fungal spore germination and infection (6, 32, 33). These nematodes also act as carriers for plant viruses that can be transmitted during feeding. The viruses attach themselves to the oesophageal lining of nematodes and directly introduced into plant cells. *Xiphinema* and *Longidorus* species transmit nepoviruses and cause Grapevine Fan leaf Virus, Tomato Ringspot Virus and *Trichodorus* species transmits tobra viruses and cause Tobacco Rattle Virus (33-37). These frequent interactions result in nematode - disease complex, where nematodes play a specific role in facilitation of infection. In particular, mechanical injuries and necrotic or diseased root tissues caused by nematode feeding are vulnerable to secondary infections by saprophytic soil organisms, leading to root rots.

4.3. Yield reductions: Plant-parasitic nematodes are hidden but possess a serious threat in protected cultivation, capable of reducing yield and increase economic losses (38, 39). In protected cultivation, yield loss due to nematodes depends on several factors like plant density, nematode density, package of practices, crop susceptibility. Root - knot nematodes (*Meloidogyne spp.*) can cause 15 % to 70 % yield loss in tomatoes and 30 to 60 % in cucumbers (40). Yield losses due to nematodes vary by crop and infestation severity.

4.4. Quality deterioration: Nematode infestation in protected cultivation structures can lead to significant quality deterioration of crops. As the feeder roots are destroyed due to nematode infection, ability of plants to absorb water and nutrients were reduced, leads to poor plant health. This can result in smaller deformed fruits, low yield; reduce shelf life, poor-quality produce and lower marketability (17, 41).

5. Management strategies

5.1. *Cultural practices*: Cultural practices are package of agricultural practices that can be used to manage nematode populations and reduce crop damage.

Crop rotation: In protected cultivation, crop rotation is an effective cultural management strategy. Crop rotation reduces the constant availability of susceptible host plants and prevents an ideal environment for nematode multiplication. Crop rotation results in breaking the persistent life cycle of nematodes and often reduces infestations (42). Crop rotation is a process of growing resistant crops alternative to susceptible crops, like growing non-host crops such as mustard, maize, or marigold (*Tagetes spp.*), that can suppress the nematode populations (43). Crop rotation not only helps in nematode management but also improves soil fertility and health. For example, growing marigold produces nematicidal compounds such as thiophenes, which are toxic to nematodes (44). Marigolds can be used as a cover crop or in a crop rotation as they produce a substance called alpha-terthienyl, aid in the reduction of root-knot nematodes, lesion nematodes, by inhibiting the hatching of nematode eggs. The nematicidal compound (alpha-tertheinyl) is only released by active, living marigold roots, because exposure to near-UV light inactivates alpha-tertheinyl when taken out of the soil. Hence, marigold extracts have no effect on nematode population (45, 46). Well - Scheduled crop rotation breaks the nematode lifecycle.

Soil solarization: Soil solarization is a non-chemical method that increases soil temperature to kill nematodes. The soil is covered with transparent plastic sheets during the peak summer months, this increases soil temperatures to nematode lethal levels. This high temperature also helps in controlling other soil-borne pathogens and kill weed seeds. This method is more effective in regions with high ambient temperatures and intense sunlight and acts as a significant disinfestation strategy. In protected cultivation structures, solarisation can reduce nematode populations by upto 80 % (47, 48).

Sanitation practices: Proper maintenance and sanitation practices can prevent the spread of nematodes. Sanitation practices include regular cleaning of tools and equipment to remove soil and plant debris, removing and destroying infested plant material and planting nematode-free seedlings (49, 50). Regular monitoring and soil testing helps in early identification of nematode infestations, allows earlier intervention. Strict sanitation measures help in reducing the inoculum levels of nematodes and other pathogens, thereby maintains a conducive environment for crop growth (51).

Fallowing: Fallowing is an effective cultural practice that can reduce the population of nematodes. The soil is allowed to rest without any planting of crops for an entire growing season, reduce the availability of feed for nematode growth and multiplication. As nematodes are obligate parasites, without these hosts, nematodes cannot complete their life cycle, results in reduction of nematode population over time (52, 53)

Green manuring: Green manuring is a process of growing green manure crops and then incorporated into the soil. This practice improves soil health and fertility and can also help manage nematode populations (54, 55). Green manure crops, such as marigolds (*Tagetes spp.*) produce compounds that are toxic to nematodes. Incorporating these crops into the soil can reduce nematode populations. Besides nematode management, they can enhance soil structure, increase organic matter content, improve nutrient availability and yield of plants (44).

5.2. *Chemical control*: Chemical nematicides such as carbofuran, fenamiphos, methyl bromide and oxamyl have been traditionally used to manage nematodes (56). Methyl bromide fumigant was extensively used to manage PPNs and soil-borne pathogens in the protected agriculture. However, concerns over environmental toxicity and regulatory restrictions have led to a shift towards bio-rational nematicides such as fluopyram and abamectin, which offer targeted action with reduced ecological impact (57). Table.1 contains the list of commercially available nematicides that can be used to control nematode infection.

5.3. *Biological control*: Plant-Microbiome interactions offer an effective, economical and environmentally-friendly alternative to chemical treatments for managing plant parasitic nematodes (PPNs). Biocontrol agents (*Trichoderma harzianum, T. viride, Purpureocillium lilacinum*, *Bacillus, Methylobacterium*) mixed with organic amendments (FYM or vermicompost) was found effective to manage plant parasitic nematodes (PPNs) in polyhouses (58-63). Prior transpanting, neem cake powder at a rate of 50-100 g/m^2 is also recommended (12, 64). Application of crushed crustacean shells in soil increases the population of chitin degrading fungi, that can act on chitin content of nematode eggs (65). *Bacillus subtilis and B. pumilus* also reduced root-knot index and increased yield in tomato and bhendi in the protected cultivation structures (66). Table. 2 explains the mode of action of various biocontrol agents used against plant parasitic nematodes (67).

Table 1. List of some commercially available nematicides along with their active ingredients, target nematodes, mode of action and manufacturers (assessed as on 22.12.2024)

Product name	Active ingredient	Target nematodes	Mode of action	Company
Vydate®	Oxamyl	Root-knot, cyst and reniform nematodes	Inhibits acetylcholinesterase, disrupting nerve impulses in nematodes	Corteva Agriscience
Nimitz®	Fluensulfone	Root-knot nematodes	Disrupts nematode motility and feeding by targeting cuticle formation	ADAMA
Mocap®	Ethoprop	Root-knot and other soil nematodes	Inhibits acetylcholinesterase activity in nematodes	AMVAC
Rugby®	Cadusafos	Root-knot and reniform nematodes	Inhibits nematode nervous system function by blocking acetylcholinesterase	FMC Corporation
Velum Prime®	Fluopyram	Root-knot nematodes	Targets energy production in nematodes by inhibiting succinate dehydrogenase	Bayer CropScience
Telone® II	1,3-Dichloropropene	Root-knot and other soil nematodes	Disrupts nematode cell membranes through fumigation	Corteva Agriscience
Counter®	Terbufos	Root-knot and reniform nematodes	Affects nematode nervous system by inhibiting acetylcholinesterase	AMVAC
Curfew®	1,3-Dichloropropene	Root-knot nematodes	Fumigant disrupting nematode cell function	AMVAC
NemaShield®	Pasteuria nishizawae (biological)	Cyst nematodes	Parasites nematode eggs and reduces population biologically	Syngenta
EcoNem®	Azadirachtin (Neem-based)	Root-knot nematodes	Blocks nematode feeding and reproduction via biological compounds	Agritechnica
Majestene®	Burkholderia rinojensis (biological)	Root-knot nematodes	Inhibits nematode reproduction and feeding through bacterial metabolites	Marrone Bio Innovations
NemOut®	Paecilomyces lilacinus (biological)	Root-knot nematodes	Parasitizes nematode eggs and prevents hatching biologically	Agri Life
DiTera®	Myrothecium verrucaria (biological)	Root-knot nematodes	Degrades nematode cuticle and disrupts feeding biologically	Valent BioSciences
Fosthiazate®	Fosthiazate	Root-knot and cyst nematodes	Disrupts nematode nervous system and inhibits acetylcholinesterase	ISK Biosciences

Table 2. List of fungal and bacterial biocontrol agents along with their modes of action against plant-parasitic nematodes (67)

Category	Organism	Main function	Key actions
Fungi	*Paecilomyces lilacinus*	Egg parasite	Produces antibiotics (leucinostatin) and enzymes (protease, chitinase) that degrade eggshells, inhibit hatching and kill juveniles.
Fungi	*Trichoderma harzianum*	Biocontrol through enzymatic degradation	Secretes lytic enzymes (chitinase, glucanase, protease) to dissolve the chitin layer of eggs and juvenile cuticles and produces toxic metabolites.
Fungi	*Trichoderma viride*	Antibiotic production	Produces antibiotics such as trichodermin, dermadin, trichoviridin and sesquiterpene heptalic acid to suppress nematode activity.
Fungi	*Pochonia chlamydosporia*	Parasitism of eggs and females	Penetrates nematode cysts through openings or eggshells, produces toxins, enzymes and a mycelial network to inhibit egg hatching and disintegrate eggshells.
Fungi	*Aspergillus niger*	Egg parasite and systemic resistance inducer	Grows on cysts or egg masses, colonizes unhatched eggs and induces systemic resistance to provide early plant protection.
Bacteria	*Pasteuria penetrans*	Parasitism of nematodes	Spores attach to nematodes, germinate and penetrate the cuticle, filling nematodes with endospores.
Bacteria	*Pseudomonas fluorescens*	Antibiotic production	Produces antibiotics (phenazines, pyoluteorin, pyrrolnitrin, pyocyanin, 2,4-diacetylphloroglucinol) to suppress nematodes.
Bacteria	*Bacillus firmus*	Indirect nematode suppression	Degrades root exudates, protects roots and produces phytohormones to reduce nematode activity.
Bacteria	*Bacillus thuringiensis*	Toxin production	Produces nematicidal proteins disrupting nematode feeding and reproduction.
Bacteria	*Bacillus subtilis*	Antibiotic production	Produces antibiotics (surfactin, iturin) to suppress nematode activity.

Conclusion and future thurst

In the face of population explosion, climate change and reducing agricultural resources, protected cultivation has gained significant importance in global crop production. Due to vast fluctuation in temperature and precipitation, climate change causes irreparable damage to crops grown in open-field conditions. Though protected cultivation is input-intensive, if offers greater crop productivity and year-round production by maintaining conducive environment for plants. Plant-parasitic nematodes pose a serious threat to the sustainable protected cultivation of vegetable in India, causing considerable yield losses and quality. Favourable microclimate (optimum temperature and humidity), monoculture of vegetables, use of nematode infected planting material increases the nematode menace to a greater degree. PPNs proliferate by 10-30 fold with population level multiplied by 5-6 times the threshold level within 1.5-2 years inside the protected structures, compared to the open fields. Prophylactic and sanitary measures in and around the protected cultivation structures can brought down the nematode population to economic threshold level. Regular monitoring of nematode population can help in identifying the early infection. To reduce the impact of these pests, a holistic integrated approach with cultural practices, biological control, chemical nematicides and novel technologies is necessary. Crop rotation, soil solarisation and stringent sanitation measures can disrupt nematode life cycles and reduce populations. Application of biocontrol agents, use of beneficial organisms and resistant cultivars offer sustainable alternatives. Though the use of chemical methods is effective, negative effect on the environment should be reduced. Advances in RNA interference (RNAi) and transgenic crops provide promising avenues for targeted nematode management. Future research should focus on developing region-specific solutions tailored to local conditions and crop systems and should examine all the interactions between PPN species in the nematode communities. Capacity building among farmers through training and education is vital to enhance the adoption of integrated pest management practices. Moreover, policy interventions promoting sustainable agricultural practices and supporting research and extension services are crucial for the widespread implementation of these strategies. By adopting a comprehensive and integrated approach, we can mitigate the impact of plant-parasitic nematodes and ensure the long-term sustainability of protected vegetable cultivation in India.

Authors' contributions

All authors contributed equally.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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