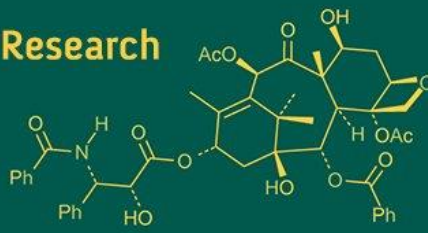


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Managing the hidden but spreading threat of plant-parasitic nematodes in India: Risk factors, dissemination dynamics, and proactive management

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Abstract

Plant-parasitic nematodes (PPNs) represent a persistent yet often underestimated challenge to Indian agriculture because of their cryptic soil-borne nature, broad host range, prolonged survival in soil, and inconspicuous above-ground symptoms. The increasing movement of planting material, changing cropping practices, climate variability, and the expansion of intensive production systems, including protected cultivation and intensive monocropping, have created new opportunities for the establishment and spread of economically important nematode species. This article analyses the major risks associated with PPNs in Indian cropping systems, key factors driving their spread, and highlights the principal dissemination pathways. It also discusses major nematode problems affecting cereals, vegetables, fruit crops, and plantation systems. It emphasizes certified nematode-free planting material, surveillance, early diagnosis, integrated nematode management, and strengthening research, extension, phytosanitary systems, and farmer awareness to support sustainable crop production and long-term nematode risk reduction. By integrating risk assessment, dissemination pathways, and mitigation strategies into a single framework, this review provides a comprehensive resource for researchers, extension personnel, and practitioners. It highlights the need to shift nematode management from reactive control to proactive prevention, thereby supporting resilient, biosecure, and sustainable agricultural production in India.

Keywords: Plant-parasitic nematodes, dissemination, integrated nematode management, planting material; plant biosecurity

Introduction

Nematodes, also referred to as roundworms or eelworms, are the most abundant invertebrate animals on the planet Earth. Among them are beneficial nematodes that play important roles in ecosystem functioning and serve as natural enemies of several economically important insect pests. In contrast, harmful nematodes parasitize humans, livestock, and plants, posing serious challenges to health and agriculture. It is estimated that nearly one million nematode species exist on Earth, of which approximately 30,000 have been scientifically described with valid taxonomic status. Only about 10% of the known nematode species parasitize plants and are collectively referred to as plant-parasitic nematodes (PPNs). Although only a small fraction of the nematode fauna utilizes plants as a food source, PPNs pose a significant risk to agriculture and horticulture by affecting a wide range of crops and causing substantial economic losses (Bhat *et al.*, 2018; Kiontke & Fitch, 2013; Kumar *et al.*, 2020) [4, 18, 19]. Understanding the risk factors associated with plant-parasitic nematodes, creating awareness, and implementing effective mitigation strategies are therefore crucial for minimizing their negative impact on crop production.

Plant-parasitic nematodes are often referred to as the hidden enemies of crop plants. PPNs are microscopic, mostly transparent animals that are generally invisible to the naked eye, making them difficult to detect without specialized equipment such as a microscope. They primarily inhabit the soil and feed on plant roots, and this concealed lifestyle enables them to inflict considerable damage before their presence is recognized. Furthermore, the symptoms of nematode infestation, including stunted growth, yellowing, and wilting, often resemble those caused by nutrient deficiencies, water stress, or other biotic and abiotic disorders. Such similarities frequently result in misdiagnosis and inappropriate management interventions.

Many plant-parasitic nematodes also possess a broad host range, allowing them to infect numerous cultivated and wild plant species, thereby increasing their persistence in agricultural and horticultural ecosystems. Nematode damage is typically chronic and progressive, resulting in a gradual decline in plant health, productivity, and yield over time. This slow and often inconspicuous nature of damage is frequently underestimated until significant economic losses have already occurred (Nicol *et al.*, 2011; Jones *et al.*, 2013; Kumar *et al.*, 2020) ^[13, 19, 21]. In addition, several PPN species can survive in the soil for extended periods in the absence of suitable host plants (Orlando & Boa, 2023) ^[22]. Collectively, these biological and ecological characteristics allow plant-parasitic nematodes to remain undetected until substantial damage has occurred, justifying their reputation as hidden enemies of crop plants.

In addition to these biological characteristics, inadequate awareness regarding nematode diseases, their modes of dissemination, and their etiology further increases the risk of nematode problems. The number of specialists engaged in nematological research, diagnostics, extension, and advisory services in India remains limited, posing a significant challenge to effective nematode management (Walia, 2024) ^[29]. Consequently, efforts aimed at creating awareness, strengthening surveillance and diagnosis, and promoting sustainable nematode management practices are constrained by the shortage of trained plant nematologists.

The development of economically damaging plant-parasitic nematode infestations is rarely the consequence of a single factor. Instead, nematode outbreaks arise from the interaction of agronomic practices, environmental conditions, and human-mediated dissemination pathways that collectively increase the probability of nematode populations exceeding economic threshold levels. Therefore, to provide a comprehensive understanding of these risks, this review presents a risk factor analysis of plant-parasitic nematodes, their major dissemination pathways, and the strategies required to reduce their impact on crop production. Understanding the risk factors also facilitates shifting nematode management interventions from reactive control to proactive prevention to support resilient, biosecure, and sustainable crop protection.

Risks of plant-parasitic nematodes

Plant-parasitic nematodes pose a multitude of risks affecting crop production. The term 'risk' rather than 'threat' is deliberately used because plant-parasitic nematodes are natural and widespread members of soil biota. PPNs are a threat to crop production; however, they may exist without posing significant risk, whereas the risk depends on the presence of a threat and vulnerability/exposure. The presence of PPNs alone does not inevitably result in crop damage. Instead, the likelihood of economic loss depends on multiple interacting factors, including nematode population density, species composition, soil biological community structure, environmental conditions, host susceptibility, and crop management practices. These factors collectively determine whether PPN populations exceed pathogenic or economic threshold levels.

PPNs feed on plant roots, disrupting water and nutrient uptake, which can lead to stunted growth, reduced yields, and, in severe cases, plant death. Nematode infestation also

reduces the quality of harvested produce, making it less marketable. Furthermore, nematode-infested plants become more vulnerable to secondary infections caused by fungi and bacterial pathogens. The breakdown of host resistance to fungal diseases in the presence of nematode infection is also well documented. The cumulative effects of yield reduction, quality deterioration, and disease complexes ultimately result in substantial economic losses to farmers (Back *et al.*, 2002; Elling, 2013; Zhang *et al.*, 2020) ^[3, 11, 31]. The hidden nature of nematode infestation, coupled with low awareness among growers, has facilitated the spread of nematode diseases into new and larger crop production areas. Emerging nematode species and virulent populations continue to pose new challenges to agriculture.

Continuous cultivation of susceptible hosts, movement of infected planting material, inadequate sanitation, poor weed management, and favourable environmental conditions provide opportunities for nematodes to survive, reproduce, and spread within and between production systems. Simultaneously, Indian agriculture is undergoing rapid transformation. Several emerging agricultural practices have further altered the nematode risk landscape in India. Protected cultivation, direct-seeded rice, intensive monocropping, and increased interstate movement of nursery stock have accelerated the dissemination and establishment of economically important nematode species (Arnell *et al.*, 2019; Phani *et al.*, 2021) ^[2, 23]. Although these approaches are intended to improve resource-use efficiency and productivity, they may inadvertently create favourable conditions for the establishment, multiplication, and dissemination of plant-parasitic nematodes if appropriate preventive measures are not implemented. Further, climate change is expected to compound these challenges by influencing nematode distribution, reproduction, and interactions with host plants (Dutta & Phani, 2023) ^[9].

The shortage of trained plant nematologists, along with limited diagnostic capacity, often results in delayed detection, misdiagnosis, and inappropriate management interventions, allowing nematode problems to spread unchecked. Consequently, understanding these risk factors are fundamental for developing preventive strategies rather than relying solely on curative management after infestations become established. Major risk factors contributing to the establishment, dissemination, and severity of plant-parasitic nematodes in Indian cropping systems are presented in Table 1.

Risks Across Major Cropping Systems

Rice-Rice and Rice-Wheat Cropping Systems

The rice-rice and rice-wheat cropping systems are among the most important cereal-based production systems in India. The rice-rice system predominates in the eastern, northeastern, and southern regions of the country, whereas the rice-wheat system is the dominant production system in north-western India. Root-knot nematode, *Meloidogyne graminicola*, has emerged as a major constraint in rice production, with infestations wreaking havoc on rice nurseries in particular. Direct-seeded rice (DSR) cultivation is being promoted as a water-saving approach. However, root-knot nematode damage is becoming severe in DSR fields. Many of the weeds, such as *Cyperus*, serve as alternate hosts and maintain nematode populations during

the off-season. Expansion of rice cultivation into non-traditional areas, inadequate weed management, and adoption of DSR without appropriate nematode preventive measures are further intensifying the problem (Bhatt & Kukal, 2015) ^[5]. The potential of *M. graminicola* to attack wheat has been reported in rice-wheat rotations (Mantelin *et al.*, 2017) ^[20]. Though major damage to wheat has not been reported, there is potential for attack depending on ambient temperature and is associated with the time of sowing of wheat crops.

The cereal cyst nematode *Heterodera avenae* is the major parasite of wheat that causes Molya disease. This nematode is primarily found in the Rajasthan-Haryana region. This nematode produces protective cysts that enclose juveniles and can survive for 4-5 years in the absence of hosts (Rao *et al.*, 2013) ^[24]. It can also spread via sand storms, contributing to the long-distance dissemination of cyst inoculum and the widespread occurrence of Molya disease in the states of Rajasthan, Haryana, Punjab, Delhi, and Uttar Pradesh.

Pulses, Oilseeds, Vegetables and Cash Crops

Although many species of root-feeding nematodes affect pulses, oilseed crops, and cash crops such as cotton, the root-knot nematodes (*Meloidogyne* spp.) remain the most destructive (Singh & Devindrappa, 2024) ^[26]. Important vegetable crops grown in India such as tomato, brinjal, cucurbits, potato, okra, and chili suffer huge losses due to root-knot nematode infestation (Khan *et al.*, 2023) ^[16]. In addition, disease complexes involving root-knot nematodes and soil-borne fungal and bacterial pathogens frequently cause severe damage to pulse, oilseed, and vegetable production.

The potato cyst nematodes (PCN), including *Globodera rostochiensis* and *G. pallida*, were assumed to be confined to the Nilgiri hills of the Southern part of the country. However, the recent comprehensive surveys unraveled their presence and high infestation levels in potato farms at high altitudes in Himachal Pradesh, Uttarakhand, and Jammu & Kashmir (Walia, 2024; Walia *et al.*, 2025) ^[29, 30]. Such findings highlight the continuing risk of long-distance dissemination of economically important nematodes into new production areas.

Protected Cultivation

Protected cultivation of vegetables is increasingly experiencing severe nematode problems, in some cases leading to abandonment of polyhouse cultivation. Although protected cultivation is intended to enhance productivity and facilitate off-season production, it also provides highly favorable conditions for nematode multiplication. Unawareness of nematode problems, combined with the construction of protected cultivation structures on nematode-infested fields, the use of nematode-infected planting materials, continuous mono-cropping or planting of good hosts, the recycling of nematode-infested materials within poly houses, improper sanitation of agricultural tools prior to use within the protected cultivation and ideal temperature and moisture conditions for nematode due to micro-irrigation systems are among the several factors which are exacerbating the nematode problems under protected cultivation (Phani *et al.*, 2021) ^[23].

Fruit Orchards and Plantation Crops

Fruit orchards and plantation crops are also at a higher risk of nematode infestation, particularly due to the inadvertent transmission of devastating nematodes via planting material across borders. Especially, nurseries of fruit crops and plantation crops have become nematode transmission hot spots. Once introduced, these nematodes become permanent problems as they are difficult to eradicate. Compared to annual crops, nematode infection in perennial woody fruit plants is usually less obvious and more difficult to diagnose. Fruit trees that are highly infested may have reduced growth, lower yield, branch tip dieback, and defoliation earlier than usual. In recent years, due to nematode and associated fungal disease complexes, very poor establishment and mortality of newly planted guava plants have been observed in several orchards across the nation. The highly virulent root-knot nematode *Meloidogyne enterolobii*, initially reported from guava orchards in Tamil Nadu, has now been detected in several guava-growing states of Southern as well as Northern regions. Its rapid spread, wide host range, ability to overcome resistance effective against other *Meloidogyne* spp., and association with guava decline have made it one of the most serious emerging nematode threats to fruit production (Khan *et al.*, 2022; Kalairasan *et al.*, 2020) ^[17, 14]. Similarly, the burrowing nematode *Radopholus similis* continues to be a major constraint in banana cultivation, causing extensive root destruction, toppling disease, and significant yield losses, while spreading primarily through infected suckers and planting material from region to region. In citrus, the citrus nematode *Tylenchulus semipenetrans*, the causal agent of slow decline disease, is widely distributed in major citrus-growing regions of the country and remains an important production constraint because of its gradual spread through infected nursery stock and contaminated soil (Kaushal *et al.*, 2026) ^[15]. Thus, nematode diseases, which were considered emerging problems a couple of years back, have become very well-established disease situations, especially under horticultural fruit crops and in protected cultivation systems.

Challenges in Nematode Management

Unlike above-ground pests and diseases, management of below-ground nematode populations is challenging due to their ability to survive in the soil for extended periods, limited visibility, their resistance to some chemical treatments, and the limited effectiveness of many control measures. Although chemical nematicides can provide suppression, their use may adversely affect soil health and the environment. Furthermore, resistant cultivars are unavailable for many economically important crops. Plant breeding programmes targeting resistance to fungal and bacterial diseases may also be compromised if nematode resistance screening is not incorporated during the early stages of cultivar development (Desaeger *et al.*, 2020; Nicol *et al.*, 2011) ^[8, 21]. Major crops might still receive attention, but minor crops and less prominent agricultural regions could suffer from neglect, as limited resources might be concentrated on the most economically significant crops. Despite the increasing importance of plant-parasitic nematodes, limited awareness, inadequate diagnostic infrastructure, shortage of trained nematologists, and the

lack of economically feasible management options continue to increase the risks posed by nematodes to Indian agriculture and horticulture.

Management tactics to reduce the risks of plant-parasitic nematodes

Effective management of plant-parasitic nematodes requires a preventive, integrated, and knowledge-based approach. Because nematodes are soil-borne, difficult to detect, and nearly impossible to eradicate once established, emphasis should be placed on preventing their introduction, reducing inoculum build-up, and minimizing their spread. Successful mitigation therefore relies on the combined efforts of farmers, researchers, extension agencies, nursery operators, and regulatory authorities. Feasible mitigation priorities against risk factors associated with PPNs are enlisted in Table 1 along with risk factors and mechanisms involved.

Awareness, Early Diagnosis and Surveillance

Low awareness among farmers and other stakeholders remains one of the major constraints in nematode management. The lower the farmers' and producers' awareness of nematode problems, the greater the risk of the spread of nematode diseases and economic losses. Lack of awareness causes low preparedness of growers, which in turn generates inadequate responses in adopting nematode management strategies. Many growers misdiagnose nematode damage as nutrient deficiency, drought stress, or fungal diseases, delaying appropriate interventions. Strengthening awareness through farmer training programmes, field demonstrations, digital advisory platforms, and participatory extension activities is essential for improving early detection and adoption of management practices (Walia *et al.*, 2025) ^[30].

Regular monitoring of fields and prompt reporting of infestations can help in timely intervention. Regular field surveillance and timely diagnosis should become an integral component of crop health monitoring. Farmers should be encouraged to inspect root systems for characteristic symptoms such as root galls, excessive branching, root lesions, cysts, or abnormal root development. However, many economically important nematodes produce inconspicuous symptoms. Therefore, laboratory diagnosis using soil and root samples is essential for species confirmation and appropriate management recommendations. Establishing accessible nematode diagnostic laboratories and strengthening surveillance networks will enable timely interventions and reduce further dissemination.

Prevention of Nematode Dissemination

Preventing the movement of nematodes is considerably more effective and economical than managing established infestations. The production and distribution of certified nematode-free planting material should therefore receive the highest priority, particularly for horticultural, plantation, and protected cultivation systems where infected nursery stock is the principal pathway for long-distance dissemination. Implementation of strict nursery sanitation protocols, certification systems, internal quarantine regulations, and phytosanitary inspections can substantially reduce the movement of nematodes across regions. Farm sanitation practices, including cleaning machinery, implements, containers, and footwear before movement between fields,

should become routine (Coyne *et al.*, 2018; Eapen *et al.*, 2024) ^[6, 10]. Similarly, preventing irrigation water from flowing from infested to healthy fields or orchards and avoiding the movement of contaminated soil can minimize secondary spread.

Integrated Nematode Management

No single management strategy provides complete or long-term suppression of plant-parasitic nematodes. Their broad host range, persistence in soil, and interaction with environmental factors necessitate an integrated approach that combines multiple complementary strategies. Integrated Nematode Management (INM) aims to maintain nematode populations below economic threshold levels while improving soil health, crop productivity, and environmental sustainability.

Cultural practices form the foundation of INM by reducing nematode survival and spread. Good Agricultural Practices (GAPs), including the use of certified nematode-free planting material, crop sanitation, balanced fertilization, proper irrigation, and cleaning of farm equipment, help prevent the introduction and dissemination of nematodes. Crop rotation with poor or non-host crops interrupts nematode life cycles, while cover crops, effective weed management to eliminate alternate hosts, destruction of infected crop residues, and soil solarization where feasible further reduce soil inoculum. Organic amendments such as farmyard manure, compost, vermicompost, green manures, biochar, and oilseed cakes provide multiple benefits beyond direct nematode suppression. Their decomposition releases compounds that inhibit nematodes while simultaneously enhancing soil organic matter, improving soil structure and water-holding capacity, and stimulating beneficial microbial communities. These changes promote natural suppression of nematodes through parasitism, predation, and competition, while improving plant vigor and resilience against nematode damage (Abd-Elgawad, 2023; Renčo, 2013) ^[1, 25].

Host resistance is among the most effective and economical management options wherever resistant or tolerant cultivars are available. Resistant varieties reduce nematode penetration and reproduction, thereby minimizing crop losses and lowering soil inoculum for subsequent crops (Starr *et al.*, 2002) ^[27]. However, resistance should be integrated with other measures to ensure long-term effectiveness. Biological management utilizes beneficial microorganisms such as *Pochonia chlamydosporia*, *Purpureocillium lilacinum*, *Trichoderma* spp., *Bacillus* spp., and *Pseudomonas* spp., which suppress nematodes through egg parasitism, antibiosis, competition, and induction of plant defenses (Dalmora *et al.*, 2026) ^[7]. Beneficial entomopathogenic nematodes (EPNs) also contribute to PPN management through their symbiotic bacteria (*Photorhabdus* and *Xenorhabdus*), whose metabolites exhibit nematicidal activity. In addition to insect pest suppression, EPNs enhance soil biological activity and nutrient cycling, providing multiple ecosystem services (Sushma *et al.*, 2024) ^[28]. Additionally, some nematodes prey on PPNs and can be introduced into the soil.

Chemical management remains an important component where nematode populations exceed economic thresholds, particularly in high-value crops. However, nematicides should be applied judiciously and integrated with cultural, biological, and host resistance strategies to minimize environmental impacts and preserve beneficial soil

organisms. Overall, integrating these complementary approaches within an IPM framework offers the most sustainable and resilient strategy for long-term nematode suppression while supporting soil health, biodiversity, and sustainable agricultural production.

Strengthening Research, Extension and Human Resource Capacity

India has relatively few trained nematologists considering its vast agricultural area, agro-climatic zones, crop diversity and population engaged in agriculture. Consequently, nematode diagnosis, advisory services, quarantine inspections, and extension activities remain inadequate in many regions. Strengthening research institutions, extension services, and quarantine systems through increased investment and specialized manpower is essential (Gaur, 2024; Walia, 2024) [12, 29].

Priority should be given to developing certified nematode-free nurseries or phytosanitary setups in different parts of the country, region-specific Packages of Practices (PoPs), mandatory nematode testing, a National nematode surveillance programme, rapid diagnostic technologies, decision-support tools, digital surveillance systems, quarantine strengthening and training extension officers. Large-scale awareness campaigns involving research organizations, State Agricultural Universities, extension agencies, private nurseries, and social media platforms should be undertaken to improve farmer awareness regarding nematode dissemination through planting material and the importance of preventive management. Finally, systematic assessment of crop losses caused by plant-parasitic nematodes should be strengthened to better quantify their economic impact, guide policy decisions, and prioritize research and extension investments.

Table 1: Major risk factors contributing to the establishment, dissemination, and severity of plant-parasitic nematodes in Indian cropping systems

S. No.	Risk factor	Mechanism increasing nematode risk	Examples/Cropping systems affected	Mitigation priority
1	Continuous cropping and monocropping	Continuous availability of suitable hosts allows rapid multiplication and gradual build-up of nematode populations above economic threshold levels.	Rice-rice systems, vegetables, cotton, banana, protected cultivation	Crop diversification, crop rotation with poor/non-host crops
2	Movement of infected nursery stock and planting material	Long-distance dissemination of nematodes through infected seedlings, suckers, tubers, rhizomes, grafts, and tissue-cultured plants contaminated during hardening.	Fruit crops like guava, pomegranate, fig, banana; potato, sugarcane, ornamentals, plantation crops	Certified nematode-free planting material, nursery accreditation, phytosanitary inspection
3	Poor field sanitation	Contaminated soil adhering to machinery, implements, containers, footwear, and tools spreads nematodes between fields.	All cropping systems	Cleaning and disinfection of machinery and equipment before field movement
4	Flood irrigation and contaminated irrigation water	Motile juveniles and infested soil particles are transported through irrigation channels; flood irrigation may disseminate nematodes from infested to healthy plants, particularly in orchards.	Fruit orchards, vegetables, rice, sugarcane	Improved irrigation management, drainage, avoiding water movement from infested to healthy fields
5	Weed reservoirs and volunteer crops	Alternate hosts maintain nematode populations during fallow periods and between cropping seasons, serving as reservoirs for reinfestation.	Rice, vegetables, orchards, pulses	Integrated weed management and removal of volunteer plants
6	Protected cultivation	Continuous cultivation of susceptible hosts under favourable temperature and moisture accelerates nematode multiplication and disease complexes.	Polyhouses, net houses, greenhouse vegetables	Soil testing before establishment, crop rotation, resistant cultivars, biological control
7	Direct-seeded rice (DSR) and water-saving production systems	Reduced flooding favours multiplication of <i>Meloidogyne graminicola</i> and increases root-knot incidence compared with conventional puddled rice.	Rice-based cropping systems	Regular monitoring, weed management, resistant cultivars, healthy nursery management, integrated nematode management
8	Climate change and weather variability	Elevated temperature, altered rainfall, drought, and extreme weather influence nematode survival, reproduction, geographical distribution, and host susceptibility.	Most cropping systems	Climate-resilient integrated nematode management and continuous surveillance
9	Lack of diagnostics and surveillance	Delayed or incorrect diagnosis allows nematode populations to remain undetected and spread before management interventions are implemented.	All crops	Strengthening diagnostic laboratories, routine soil testing, surveillance networks
10	Limited awareness and trained human resources	Low farmer awareness and insufficient diagnostic expertise result in misdiagnosis, delayed intervention, and poor adoption of management practices.	Nationwide	Capacity building, extension programmes, digital advisory services, farmer training

Table 2: Major plant-parasitic nematode risks in Indian cropping systems and their primary routes of spread.

S. No.	Cropping system	Major nematode species	Principal crop hosts	Principal crop hosts	Primary route(s) of spread
1.	Rice	<i>Meloidogyne graminicola</i> , <i>Hirschmanniella oryzae</i> , <i>Aphelenchoides besseyi</i>	Rice	Rice-associated grasses (graminae weeds), sedges, aquatic weeds, volunteer rice	Infected nursery seedlings, irrigation water, contaminated soil, seed (white-tip nematode), farm machinery
2.	Wheat	<i>Heterodera avenae</i> , <i>Pratylenchus thornei</i> , <i>Anguina tritici</i>	Wheat, barley, oats	Cereal grasses, grassy weeds, volunteer cereals	Infested soil, cysts, seed galls (<i>Anguina tritici</i>), irrigation water, machinery
3.	Rice-Wheat	<i>M. graminicola</i> , <i>H. avenae</i> , <i>Pratylenchus</i> spp.	Rice, wheat	Grassy weeds, sedges, volunteer cereals, rice-associated weeds	Soil movement, irrigation water, machinery, infected planting material
4.	Pulses	<i>Meloidogyne incognita</i> , <i>Rotylenchulus reniformis</i> , <i>Pratylenchus</i> spp.	Chickpea, pigeonpea, mungbean, urdbean	Broadleaf weeds, pigweeds, purslane, goosefoot, volunteer legumes	Infested soil, irrigation water, contaminated tools, infected seedlings
5.	Oilseeds	<i>Meloidogyne incognita</i> , <i>Rotylenchulus reniformis</i>	Mustard, sunflower, groundnut, sesame	Broadleaf weeds, sedges, volunteer oilseed crops	Soil, irrigation water, infected planting material, machinery
6.	Cotton	<i>Rotylenchulus reniformis</i> , <i>Meloidogyne incognita</i>	Cotton	Broadleaf weeds, pigweeds, purslane, nut sedges, volunteer cotton	Infested soil, irrigation water, infected seedlings, agricultural equipment
7.	Sugarcane	<i>Pratylenchus zae</i> , <i>Meloidogyne javanica</i> , <i>Helicotylenchus dihystra</i>	Sugarcane	Grasses, nut sedges, perennial grassy weeds	Infected setts, contaminated soil, irrigation water, machinery
8.	Potato	<i>Globodera rostochiensis</i> , <i>G. pallida</i> , <i>Meloidogyne incognita</i>	Potato	Solanaceous weeds, volunteer potato, volunteer tomato	Seed tubers, cyst-infested soil, machinery, irrigation water
9.	Vegetable crops	<i>M. incognita</i> , <i>M. javanica</i> , <i>M. enterolobii</i> , <i>R. reniformis</i>	Solanaceous, cucurbitaceous, cruciferous and other vegetables	Broadleaf weeds, nut sedges, solanaceous weeds, volunteer vegetables	Infected nursery seedlings, potting media, soil, irrigation water, contaminated tools
10	Fruit orchards	<i>Meloidogyne</i> spp., <i>Radopholus similis</i> , <i>Tylenchulus semipenetrans</i> , <i>R. reniformis</i>	Banana, citrus, grapevine, guava, pomegranate	Perennial grasses, sedges, broadleaf weeds, volunteer fruit seedlings	Infected nursery stock, soil attached to roots, irrigation water, machinery
11	Plantation crops	<i>Radopholus similis</i> , <i>Pratylenchus coffeae</i> , <i>Meloidogyne</i> spp.	Banana, coconut, arecanut, coffee, tea, black pepper	Perennial grasses, creeping weeds, sedges	Infected suckers/seedlings, contaminated soil, irrigation water, farm implements
12	Spice crops	<i>Meloidogyne incognita</i> , <i>Radopholus similis</i>	Ginger, turmeric, black pepper	Broadleaf weeds, sedges, perennial weeds	Infected rhizomes, planting material, contaminated soil, irrigation water
13	Floriculture & ornamentals	<i>Meloidogyne</i> spp., <i>Aphelenchoides</i> spp.	Ornamentals and flowering crops	Broadleaf weeds, sedges, nursery weeds	Infected planting material, potting media, irrigation water, tools

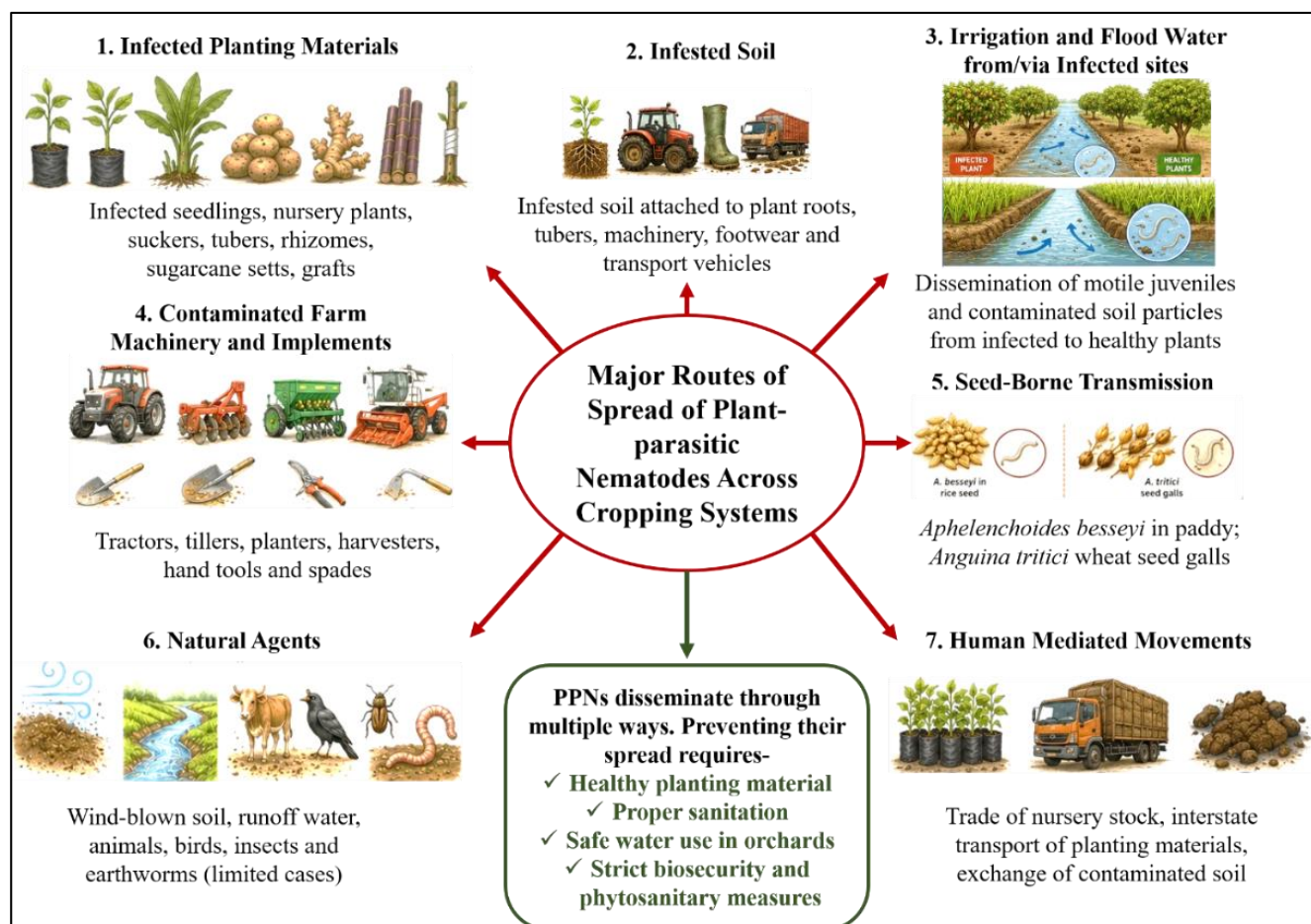


Fig 1: Major routes of spread of plant-parasitic nematodes across cropping systems.

Plant-parasitic nematodes are disseminated through multiple natural and human-mediated pathways. Major routes include (1) infected planting material, (2) infested soil (3) irrigation and flood water, (4) contaminated farm machinery and implements; (5) seed-borne transmission in crops such as rice (*Aphelenchoides besseyi*) and wheat (*Anguina tritici*); (6) natural agents including wind-blown soil, runoff water, animals, birds, insects, and earthworms; and (7) human-mediated movement through trade of nursery stock, interstate transport of planting material, and exchange of contaminated soil. Preventing nematode spread requires the use of certified clean planting material, sanitation of equipment, safe irrigation practices, and strict on-farm biosecurity measures.

Conclusion

Plant-parasitic nematodes remain one of the most underestimated constraints to sustainable agriculture in India because of their hidden nature, efficient dissemination, and persistence in soil. Many of the risks associated with nematode-induced crop losses can be substantially reduced through preventive interventions, including the use of certified nematode-free planting material, routine surveillance and diagnostics, improved sanitation, integrated weed management, and adoption of integrated nematode management practices. Therefore, identifying and mitigating the key risk factors governing nematode establishment and spread should form the cornerstone of future nematode management programmes, shifting the emphasis from reactive control to proactive risk reduction. Such a preventive, integrated, and knowledge-driven approach will be critical for safeguarding crop productivity, protecting soil health, and ensuring the long-term sustainability of Indian agriculture.

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Authors' Contributions

C.G.B. conceptualized the study, prepared the original draft, and revised the manuscript. A.K. contributed to writing and editing the manuscript. All authors read and approved the final version of the manuscript.

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