Gesunde Pflanzen (2023) 75:193–209
https://doi.org/10.1007/s10343-022-00679-2

REVIEW ARTICLE / ÜBERSICHTSBEITRAG

Bio-organics Management: Novel Strategies to Manage Root-knot Nematode, *Meloidogyne incognita* Pest of Vegetable Crops

Amir Khan[1] · Gufran Ahmad[2] · Mohammad Haris[2] · Abrar Ahmad Khan[1]

Received: 15 February 2022 / Accepted: 3 May 2022 / Published online: 29 May 2022

Abstract

Root-knot nematodes (*Meloidogyne* spp.) are sedentary endoparasites and soil-borne pathogens worldwide. *M. incognita* is one of the most devastating and dominant species among them causing economic yield losses in almost all vegetables and other agricultural crops in the world. Current management strategies against *M. incognita* are not sufficient. However, from the last decades, utilization of nematicides has been increasing to manage this pest due to which environmental and human health issues arises. Bio-organic approaches are the best alternatives to nematicides, including biological agents and organic matters. In bio agents both arbuscular mycorrhizal and nematophagous fungi have a potent ability to manage plant-parasitic nematodes by inducing systemic resistance and activation of pathogenesis related (PR) genes in inoculated plants against nematodes, whereas nematophagous fungi trap nematodes for their feeding and killing them. Soil application of organic matters *viz*., botanical extract, oil cakes and agricultural wastes both *in vitro* and *in vivo* is also useful. Botanical extracts, oil cakes, kill nematodes by releasing secondary metabolites and inhibiting the movement of juveniles in the soil. Researchers from all over the world engage in evolving eco-friendly approaches that enhance and sustain the vegetable and agricultural production against this pest and keep it below the threshold level without affecting beneficial soil microbiota. In the future, such environment benign approaches have become an active field of research that adds new knowledge for their success against pest management, and enhancement of agricultural production for the human population.

Keywords Meloidogyne incognita · Arbuscular mycorrhizal · Nematophagus fungi · Induced systemic resistance · Pathogenesis related genes · Botanical extracts · Oil cakes

✉ Amir Khan
amirahamadgh7682@gmail.com

[1] Plant Pathology and Nematology Section, Department of Botany, Aligarh Muslim University, 202002 Aligarh, UP, India

[2] Section of Environmental Botany, Department of Botany, Aligarh Muslim University, 202002 Aligarh, India

Biologisch-organische Bewirtschaftung: neue Strategien zur Bekämpfung des Wurzelgallennematoden *Meloidogyne incognita* als Schädling von Gemüsekulturen

Zusammenfassung

Wurzelgallennematoden (*Meloidogyne* spp.) sind sesshafte Endoparasiten und bodenbürtige Krankheitserreger weltweit. *M. incognita* ist eine der verheerendsten und dominantesten Arten unter ihnen und verursacht wirtschaftliche Ertragseinbußen bei fast allen Gemüsearten und anderen landwirtschaftlichen Kulturen in der Welt. Die derzeitigen Strategien zur Bekämpfung von *M. incognita* sind nicht ausreichend. In den letzten Jahrzehnten wurden jedoch immer mehr Nematizide zur Bekämpfung dieses Schädlings eingesetzt, was zu Problemen für die Umwelt und die menschliche Gesundheit führte. Bio-organische Ansätze sind die beste Alternative zu Nematiziden, einschließlich biologischer Wirkstoffe und organischer Stoffe. Bei den biologischen Wirkstoffen haben sowohl arbuskuläre Mykorrhizapilze als auch nematophage Pilze die Fähigkeit, pflanzenparasitäre Nematoden zu bekämpfen, indem sie eine systemische Resistenz und die Aktivierung von PR-Genen (*pathogenesis related*) in den beimpften Pflanzen gegen Nematoden induzieren, während nematophage Pilze die Nematoden einfangen, um sie zu fressen und zu töten. Der Einsatz von organischen Stoffen im Boden, d. h. Pflanzenextrakten, Ölkuchen und landwirtschaftlichen Abfällen, ist sowohl *in vitro* als auch *in vivo* nützlich. Pflanzenextrakte und Ölkuchen töten Nematoden ab, indem sie sekundäre Metaboliten freisetzen und die Bewegung von Jungtieren im Boden hemmen. Forscher aus der ganzen Welt arbeiten an der Entwicklung umweltfreundlicher Ansätze, die die Gemüse- und Agrarproduktion gegen diesen Schädling verbessern und aufrechterhalten, ohne die nützliche Bodenmikrobiota zu beeinträchtigen. In der Zukunft werden solche umweltfreundlichen Ansätze ein aktives Forschungsgebiet sein, das neue Erkenntnisse über den Erfolg bei der Schädlingsbekämpfung und der Verbesserung der landwirtschaftlichen Produktion für die menschliche Bevölkerung liefert.

Schlüsselwörter Meloidogyne incognita · Arbuskuläre Mykorrhizapilze · Nematophage Pilze · Induzierte systemische Resistenz · Mit der Pathogenese verbundene Gene · Pflanzenextrakte · Ölkuchen

Abbreviations

GalNac	D-galactosamine N-acetyl
GCs	Giant cells
J2s	Second stage juveniles
MAMPs	Microbe-associated molecular pattern
MTI	MAMPs triggered immunity
PPNs	Plant parasitic nematodes

Introduction

The rhizosphere has numerous soil-borne microorganisms interacting with plant roots either antagonistically or synergistically and with other associated microbes. Few of them are helpful to plants and the rhizosphere, whereas some are harmful, i.e., act as biotic stressors. Plant-parasitic nematodes (PPNs) are the most critical and common soil-borne pathogens that affect the global agricultural industry (Kenney and Eleftherianos 2016). At present, about 4100 species of PPNs have been identified, which exhibit a negative impact on the agricultural industry by deteriorating numerous vegetable crops, including eggplant, okra, tomato, chilli, carrot, spinach, cabbage, cauliflower, etc. (Decraemer and Hunt 2013; Chariou and Steinmetz 2017). Numerous nematologists categorized top 10 PPNs that have a global economic impact; these are root-knot nematodes (*Meloidogyne* spp.), root lesion nematode (*Pratylenchus* spp.), cyst nematodes (*Heterodera and Globodera*), burrowing nematode (*Radopholus similis*), pine wilt nematode (*Bursaphelenchus xylophilus*), stem and bulb nematode (*Ditylenchus dipsaci*), reniform nematode (*Rotylenchulus reniformis*), rice white tip nematode (*Aphelenchoides besseyi*), false root-knot nematode (*Nacobbus aberrans*) and dagger nematode (*Xiphinema index*-the virus vector nematode) (Jones et al. 2013). Among these, root-knot nematodes (*Meloidogyne* spp.) are the most dangerous and economically important.

Meloidogyne incognita and Its Status On Vegetable Crops

Root-knot nematodes (*Meloidogyne* spp.) belonging to the family, Heteroderidae Order, Tylenchida are considered as highly adaptive, widespread and sedentary obligate endoparasites among all PPNs that completely depend on the host for their survival and reproduction (Khan 2008). Globally, >100 species of root-knot nematodes (*Meloidogyne* spp.) have been identified with more than 3000 host plants, including vegetables and fruits. Four species *viz.*, *M. incognita, M. javanica, M. arenaria* and *M. hapla* are major and more pathogenic to cause major losses to agricultural crops worldwide up to 90% and predispose the crops to other soil-borne pathogens (Hunt and Handoo 2009; Lunt et al. 2014).

According to Ghule et al. (2014), 14 species of root-knot nematodes have been identified from different areas of India. Out of different species of root-knot nematodes, *M. incognita* was the dominant species in agricultural fields that causes major loss and reduces the quality of vegetable crops *viz*., okra, eggplant, tomato, and spinach. However, the occurrence of root-knot disease in vegetable fields in different areas of India was predominant due to which vegetable qualities and production are affected. Other species *viz*., *M. javanica, M. arenaria* and *M. graminicola* are also common and pathogenic (Ghule et al. 2014). However, *M. hapla* is found in temperate/cooler areas (Escobar et al. 2015).

Annual vegetable losses reach up to 19.6%, whereas annual crop damage is up to the tune of Rs. 242.1 billion due to PPNs in India (Ahmad et al. 2021). Globally, an average of 10% annual yield loss is recorded in vegetables due to root-knot nematodes. However, much higher percentage losses have been recorded depending upon nematode species, and their population in the soil, locality, and crop species (Collange et al. 2011). Jain et al. (2007) reported yield losses up to 18.20%, 16.67%, 14.10%, 21.35%, 10.54%, and 27.21% in cucurbits, brinjal, okra, jute, rice, and tomato, respectively in India due to root-knot nematode, *M. incognita* (Table 1).

Life Cycle of *M. incognita* On Vegetable Crops

The life cycle of *M. incognita* i.e., from egg to mature female is completed in 25 days at 27◦C, but this period is altered by the availability of suitable host, soil moisture (lesser extent), and soil temperature (widely) (Fig. 1). It started with the hatching of second-stage juveniles (J2s), named to be an infective stage; a stage that initiates the process of infection into the host roots (Rawal 2020). However, CO_2 is a major root diffusate that plays a significant role in long-distance attractant for J2s of *M. incognita* and other PPNs (Robinson 2002). After attaching with the host roots, J2s secret certain proteins or enzymes *viz*., endoxylanases, cellulases (endoglucanases), polygalacturonases and pectatelyases from their sub ventral glands into the roots (Davis et al. 2011; Wieczorek et al. 2014; Perry and Moens 2011). Some of these secreted enzymes change the components of the host plant's cell wall or inhibit the host cell cycle, increase degradation of host cell protein, and reduce defence and transcriptional regulation (Akker and Birch 2016). Some parasitic enzymes digest the cellular component of the host plant, establish the permanent feeding site of nematodes within the host roots and help in the formation of giant cells (GCs) (Shakeel et al. 2020). GCs become galls or knots by hypertrophy and hyperplasia and are source of mineral nutrients for nematodes till reproduction. The formation of galls in the roots (Fig. 2) damage the vascular system of the host plant and inhibits its ability to absorb essential mineral elements and water from the soil that ultimately leading to wilting and yellowing of plant (Gao et al. 2016; Lee and Kim, 2016; Jamal et al. 2017). Such infections on the plants also increase the plant's susceptibility to other soil-borne pathogens and form disease-complexes with other harmful soil microbes (Zhou et al. 2016).

Table 1 Losses on vegetable crops due to various species of root-knot nematodes

Root-knot nematode species	Host crop	Losses (%)	Country	References
Meloidogyne incognita	Tomato	40%	India	Singh and Kumar (2015)
Melodogyne spp	Chilli Radish	8–23% 8–20%	India	Gowda et al. (2017)
Meloidogyne incognita	Ivy gourd	35.09%	India	Basumatary et al. (2018)
Meloidogyne incognita	Cucumber	66.84% in poly house	India	Bhati and Baheti (2021)
Meloidogyne spp	Okra	480.00 million/annually approx	India	Jain et al. (2007)
Meloidogyne spp	Tomato	24–38%	Pakistan	Mukhtar (2018)
Meloidogyne spp	Tomato	30%	Nepal	Rawal (2020)
Meloidogyne spp	Tomato	80% approx	Turkey	Kaskavalci (2007)
Meloidogyne incognita	Tomato	2.3%	Ethiopia	Sikora and Fernandez (2005), Wesemael et al. (2011)
Meloidogyne spp	Potato	10%	Egypt	Shaltoot (2001)
Meloidogyne spp	Carrot	45%	USA	Widmer et al. (1999)
Meloidogyne spp	Sponge gourd	Rs. 547.5 billion annually	India	Chandra et al. (2010), Jain et al. (2007)
Meloidogyne incognita	Bitter gourd	36.72%	India	Darekar and Mhase (1988)
Meloidogyne incognita	Pointed gourd	44%	India	Verma and Anwar (1996)

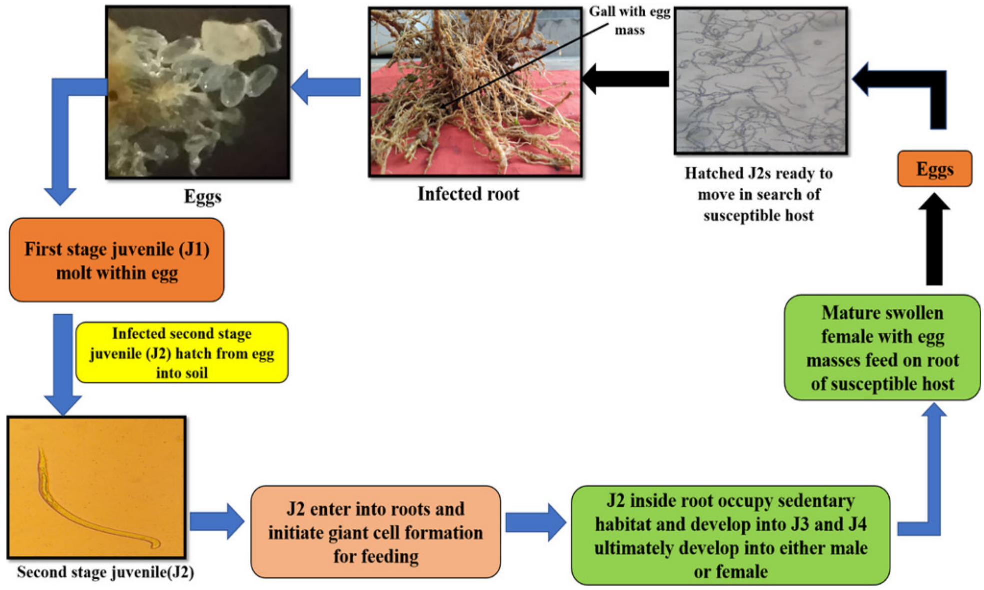

Fig. 1 Life cycle of root-knot nematode *M. incognita*

Fig. 2 Root samples of various vegetable crops infected with *M. incognita*, **a** Root of okra, **b** Beet root, **c** Spinach, **d** Cucurbita, **e** Tomato, and **f** Eggplant root

Bio-organics Management

Continuous use of nematicides increases the environmental pollution and human health issues. Such issues enhance the utilisation of eco-friendly like bio-organic approaches that could be a grateful for managing *M. incognita* and sustain vegetables production. Although, cultural methods are traditional and facing more restrictions due to the wide host range of *M. incognita* and the existence of mixed populations of different species of genus, *Meloidogyne* in the field (Xiang et al. 2018), uses of resistant cultivars have been also a successful management tool to protect the crop, but it has been found that certain new species of root-knot nematodes break this resistance *viz.*, *M. enterolobii* (Xiang et al. 2018; Hajihassani et al. 2019). Bio-organics management as eco-friendly management included biotic, application of microbes in both *in vitro* and *in vivo* conditions and abiotic/organic approaches, uses of botanicals, oil cakes and agricultural wastes. Besides these, plants themselves also manage several types of soil-borne pathogens, including

M. incognita, by releasing various root exudates, namely amino acids, sugars, organic acids etc. (Bell et al. 2019).

Biotic Approaches Against *M. incognita*

In biotic approaches, application of living agents' *viz.*, fungi (arbuscular and nematophagous fungi), bacteria or other microbes are considered. These bio agents consists of factors or substances that improve plant growth by inducing resistance gene and control PPNs is another best tool which replaces the chemicals in agriculture (Forghani and Hajihassani 2020). Several studies suggested that synthetic pesticides or chemicals create environmental issues. The excessive amount of chemicals in the soil reduces its fertility, builds soil disintegration, and has negative impacts on human health. Bio-agents will help the plants to control or reduce the harmful effects of soil-borne pathogens, including root-knot nematode, *M. incognita* by interacting with the roots of plants (Forghani and Hajihassani 2020). Other activities like facilitating the resources acquisition, production of plant hormones (gibberellins and cytokinin), lytic enzymes and antibiotics also are done by beneficial microbes within the soil (Glick 2012). Some of the mechanisms were involved to facilitate the endogenous defence at the gene level by activating the genes related to pathogenesis (PR-genes), PR-1, PR-1b, PR-3, 5, salicylic acid (SA)-dependent genes related to pathogenesis of the systemic acquired resistance (SAR) and other genes that kill *M. incognita*. Few enzymatic activities like endochitinase and glucanases were also increased against *M. incognita* in the roots of pre-treated inoculated plants (Molinari and Leonetti 2019).

Arbuscular Mycorrhizal Fungi (AM Fungi) as Bio-control Agents Against *M. incognita*

Arbuscular mycorrhizal fungi (AM fungi) are found in greater than 80% of almost all soil plants species as obligate root symbionts. They increase uptake of mineral elements in their host plant in exchange of carbon, enhance plant growth and reduce stress in plants (biotic and abiotic stress) (Smith et al. 2010; Vos et al. 2012). These fungi also help plants to increase water uptake and reduce metal toxicity in the soil (Kerry and Hominick 2002). Several studies, *in vitro* and *in vivo* revealed the protective effects of AM fungi against root-knot nematodes in some plants *viz.*, in tomato against *M. incognita*, in coffee against *M. exigua, M. cofeeicola* and in banana against *X. index* (Vos et al. 2012; Koffi et al. 2013). AM fungi also facilitated the plants to produce certain compounds against PPNs and interfered in the secretion and production of root diffusates that attract PPNs (Teillet et al. 2013).

Mechanisms of Action of AM Fungi Against *M. incognita*

Enhanced Plant Tolerance

Increased Nutrients Uptake AM fungi in their host plant facilitate the uptake of certain macro elements such as phosphorus, nitrogen, some micro element *viz.*, zinc and water from the soil; in return, they take carbon from their host (Smith and Smith 2011; Baum et al. 2015). However, it has been found the plant that colonized by AM fungi showed higher phosphate uptake and less susceptibility to *M. incognita* in contrast to the plant that was not colonized by AM fungi. According to Pettigrew et al. (2005), higher nutrient uptake in cotton plant fields helped to reduce or control sedentary semi-endoparasitic nematode, *Rotylenchulus reniformis*.

Changed Root Morphology In addition, to increase nutrients uptake, AM fungi inoculated plants showed higher root branching, growth, and led to change in root morphology like tap root than fibrous root from which plant improve their nutrient acquisition and better biomass (Gutjahr and Paszkowski 2013; Yang et al. 2014). According to Vos et al. (2014), mycorrhizal treated plant shows better root growth and branching, leading to resistant against *M. incognita*. AM fungus *Funneliformis mosseae* protect the banana plant from migratory endoparasitic nematodes *Pratylenchus coffeae* and *Radopholus similis* by increasing or changing root morphology (Elsen et al. 2003b). However, it has been reported by some researchers that increased in root branching lead to an increase in infection sites that negatively affect host plant. Depending on the plant species and PPNs *viz.*, root-knot nematode, *M. incognita* and cyst nematodes (*Heterodera* spp.), prefer lateral root formation sites and elongation zones, whereas *R. similis*, prefers primary roots due to presence of secretory substances in these zones (Curtis et al. 2009; Elsen et al. 2003a).

Challenges for Nutrients, Space and Infection Sites

Competition for space, host nutrients and infection sites is found among microbes which occupy the same habitat and have the same feeding requirements in an ecological niche when resources are limited such as carbon (C) (Vos et al. 2014). Competition for nutrients like carbon becomes the main mechanism for AM fungi-mediated bio-control (Jung et al. 2012). AM fungi treated plants do better photosynthesis in which carbon demand increase such higher carbon demand inhibits pathogen growth.

Competition for the available space suggested that high level of AM fungi colonization within the host roots resulted in a higher level of bio-control activity against

M. incognita (Vierheilig et al. 2008). However, a bio-control activity was observed when both AM fungi and *M. exigua* were inoculated in the coffee plants (Alban et al. 2013). Vigo et al. (2000) found that the AM fungi treated roots reduced the number of infection sites, revealing that more infections will be by pathogen infections.

Effect of Induced Systemic Resistance

It has been found that inoculation of tomato plants with AM fungi increased the systemic resistance against *M. incognita* (De la Peña et al. 2006). Plants have a specialized pattern called microbe-associated molecular patterns (MAMPs) between harmful and beneficial fungi (Zamioudis and Pieterse 2012). Recognition receptors on MAMPs help to switch on the MAMPs triggered immunity (MTI) which initiate the defence in plant against further invasion by PPNs (Jones and Dangl 2006). Activation of MTI responses leads to hormonal and transcriptional changes in their host plant (Schouteden et al. 2015). Fiorilli et al. (2011) evaluated the changes in the transcriptome of tomato plants when colonized by AM fungi *F. mosseae*. They reported significant modification in genes both in shoots and roots, with the highest variations in both primary and secondary metabolism and defence response against biotic stimulus such as root-knot nematode, *M. incognita*. AM fungus *F. mosseae* was involved in the activation of the root-specific 9-lipoxygenase (9-LOX) and isoleucine conjugation of the jasmonic acid (JA-Ile) pathway. Activation of early MTI-response leads to the induction of jasmonate-linked 9-LOX-pathway that inhibit the development and growth of root-knot nematode. Expression of the 9-LOX gene (ZmLox3 gene) in maize plants was beneficial and enhanced protection against *M. incognita* (Gao et al. 2008). It has been observed that external JA-application and study of changes or mutants in the JA-pathway were found to initiate the resistance in host plant against PPNs (Fan et al. 2015; Fujimoto et al. 2011). Li et al. (2006) observed that the class III chitinase gene of *Glomus versiforme* in the roots of grapevine was activated during the infection by *M. incognita*. Such report strongly recommends that AM fungi's class III chitinases gene provides resistance against the PPNs. Though the eggs with chitin are affected more by the chitinase enzymes, they also reduce the egg masses and number of the females of root-knot nematodes (Chan et al. 2015). However, future research should be focused on demonstrating the mechanism of action of chitinases against PPNs, with attention on the metabolome and proteome AM fungi-associated changes.

Altered Rhizospheric Interactions

Alteration in the release of root exudates affects the microbial community in the vicinity of roots and affects interactions between pathogen and plant (Lioussanne 2010). Some reports suggested that the colonization of a plant by AM fungi increased the diversity of beneficial microbes like *Streptomyces* species, fluorescent pseudomonads, chitinase-producing actinomycetes, and facultative anaerobic bacteria (Nuccio et al. 2013; Miransari 2011). These microbes showed antagonistic activity against root-knot nematodes and other PPNs, either by egg-parasitizing fungal activity or nematode-trapping activity or also by induction of the plant defence (Zamioudis and Pieterse 2012). Secretory substances from the roots of mycorrhizal plants were involved in the activation of the beneficial fungus *Trichoderma* spp. having bio-control activity against root-knot nematodes and attraction of plant growth-promoting bacteria *Pseudomonas fluorescence* (Druzhinina et al. 2011; Sikora et al. 2008) (Fig. 3).

Nematophagous Fungi as Bio-control Agents Against *M. incognita*

"Nematophagous fungi" are referred to a various group of fungi that feed and colonize on the nematodes. Some fungi parasitize nematodes are obligatory, whereas most of them are as facultative saprophytes of nematodes (Lopez-Llorca et al. 2008). These fungi belong to various phylogenetic groups, Zygomycota, Chytridiomycota, Ascomycota

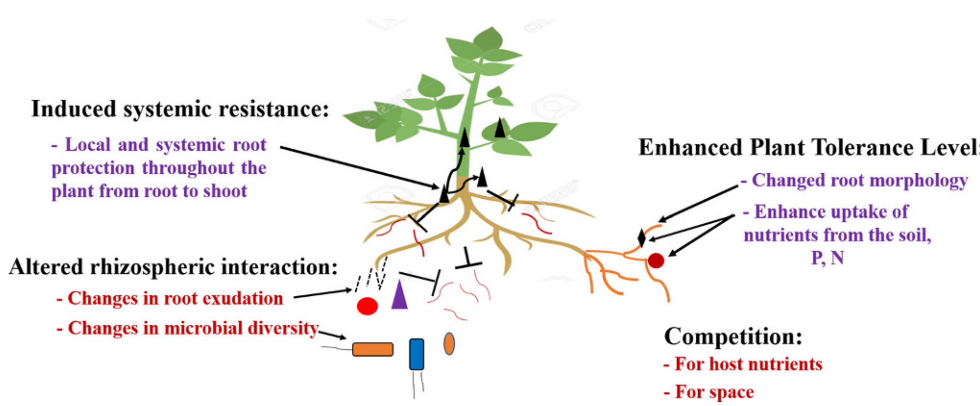

Fig. 3 Mechanisms of action of arbuscular mycorrhizal fungi as bio agents against root-knot nematode, *M. incognita*

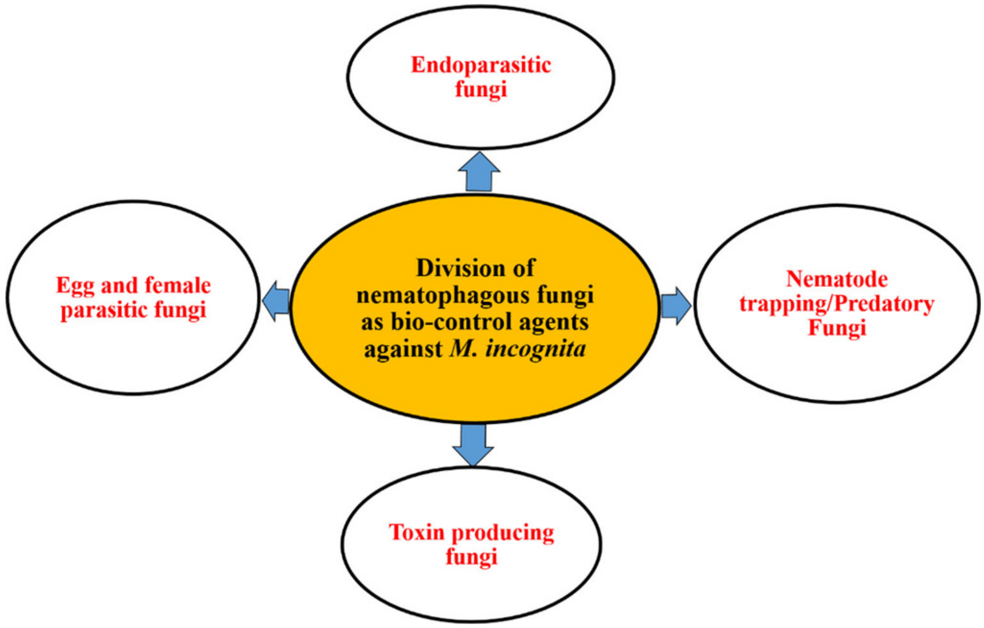

Fig. 4 Division of nematophagous fungi as bio agents against root-knot nematode, *M. incognita* in vegetable crops

and Basidiomycota. The fungi of zygomycetes group are entirely dependent on water and encircle soil particles in searching of nematode hosts by their swimming zoospores. Based on the mechanisms of action against nematodes, nematophagous fungi can be classified into four major groups: (I) nematode-trapping fungi (predatory fungi), (II) endoparasitic fungi, (III) egg-parasitic fungi and (IV) toxin-producing fungi (Fig. 4; Table 2).

Predatory/nematode Trapping Fungi

Fungi of this group are soil-borne that trap moving stages of *M. incognita* with the help of various trapping structures of different size and shapes as shown in Table 2**.** The predatory nature of these fungi exists in the presence of nematodes prey and produces various types of trapping devices such as adhesive network, knobs, and columns, non-constricting and constricting rings through which they capture nematodes (Zhang and Hyde 2014). It was found that trapping fungi also have the capability to release certain compounds as antimicrobial and nematicidal properties, pleurotin (*Nematoctonus robustus, N. concurrens*) or linoleic acid (*Arthrobotrys oligospora* and *A. conoides*) *viz*., *A. superba* secret a compound for trapping J2s of *M. incognita* (Hallmann et al. 2009). However, soil applications of various substances like organic compounds (chopped leaves, oil cakes) and glucose increases the trapping ability of nematode-trapping fungi (Duddington 1962; Cooke 1962). Nematode trapping ability of *Drechslerella stenobrocha* strain AS6.1 was enhanced by soil application of abscisic acid (ABA) and inhibited by nitric oxide (NO) (Xu et al. 2011). It has been found that *A. dactyloides* efficiently trapped pathogenic juveniles of *M. graminicola* compared to *Dactylella brochopaga* and *Monacrosporium eudermatum* (Hallmann et al. 2009).

Endoparasitic Fungi

Endoparasitic fungi infect *M. incognita* using their spores (conidia or zoospores) and complete their vegetative phase inside nematode (Lopez-Llorca et al. 2008). However, as compared to trapping fungi, endoparasitic fungi consist of either a limited saprophytic phase or no saprophytic phase (Moosavi and Zare 2012). The conidia of endoparasitic fungi adhere to the nematode cuticle with the help of hyphae and kill them. Other endoparasitic fungi like *Nematoctonus* spp., *Drechmeria coniospora* and *Haptocillium balanoides*, are extensively studied and have a potent practical approach for controlling PPNs such as *Meloidogyne* spp. compared to nematode trapping fungi of which *D. coniospora* is the most studied against root-knot nematode (Viaene et al. 2006). However, *in-vitro* studies showed that *Hirsutella rhossiliensis* caused the death of *M. incognita* J2s in 2 days, whereas *Ditylenchus dipsaci* in 4 days (Cayrol et al. 1986).

Egg Parasitic Fungi

Fungi parasitizing eggs, female and other stages of PPNs, attracted more attention due to their potent approach in controlling economically important nematodes *viz*., root-knot nematode, *M. incognita* and cyst nematodes (*Heterodera* spp.). These fungi infect their host nematodes with the help of specialized structures called zoospores, appressoria, lateral mycelial branches and penetration peg (Lopez-Llorca et al. 2008). *Paecilomyces lilacinus, Pochonia chlamydosporia* and *Lecanicillium psalliotae* are the

Table 2 Classification of nematophagous fungi according to their mode of action against different stages of plant-parasitic nematodes (Li et al. 2015; Moosavi and Zare 2012)

Phylum	Name of fungi	Fungal group	Infective structures against PPNs
Ascomycota fungi	*Drechslerella stenobrocha*	Nematode-trapping fungi	Constricting rings
	Arthrobotrys oligospora, Arthrobotrys conoides, Arthrobotrys musiformis, Arthrobotrys superba	Nematode-trapping fungi	Adhesive networks
	Dactylellina haptotyla	Nematode-trapping fungi	Adhesive knobs and/or Non-constricting rings
	Hirsutella minnesotensis	Endoparasitic fungi	Adhesive conidia
	Drechmeria coniospora	Endoparasitic fungi	Adhesive conidia
	Harposporium cerberi	Endoparasitic fungi	Ingested conidia
	Pochonia chlamydosporia	Egg- and female-parasitic fungi	Appressoria
	Lecanicillium psalliotae, Lecanicilium lecanii	Egg- and female-parasitic fungi	Appressoria
	Paecilomyces lilacinus	Egg- and female-parasitic fungi	Appressoria
Basidiomycota fungi	*Pleurotus ostreatus*	Toxin-producing fungi	Toxic droplets
	Coprinus comatus	Toxin-producing fungi	Toxin, spiny structures
	Nematoctonus haptocladus	Endoparasitic fungi	Adhesive spores
Oomycota fungi	*Nematophthora gynophila*	Egg- and female-parasitic fungi	Zoospores
	Myzocytiopsis enticularis, M. humicola	Endoparasitic fungi	Zoospores
	Haptoglossa heterospora	Endoparasitic fungi	Gun cell, injection
Zygomycota fungi	*Stylopage hadra*	Nematode-trapping fungi	Adhesive hyphae
	Cystopage cladospora	Nematode-trapping fungi	Adhesive hyphae

most frequently isolated and promising bio-control agents against *M. incognita* among all egg parasitic fungi (Li et al. 2015). The egg shell layer of *M. incognita* consists of chitin and protein organized in an amorphous and microfibrillar structure degraded by several hydrolytic enzymes like proteases and chitinases of egg parasitic fungi (Yang et al. 2007a).

Toxin Producing Fungi

The toxin-producing fungi are the most prominent and more potent against PPNs. These fungi release toxins that show nematicidal properties and paralyse the nematodes before penetration of fungal hyphae through nematode cuticle (Lopez-Llorca et al. 2008). Fungus, *Pleurotus ostreatus* released a potent toxin named trans-2-decenedioic acid, showing both *in vivo* and *in vitro* nematicidal properties and quickly paralysed the PPNs (Luo et al. 2004).

Besides the four groups of nematophagous fungi, some other fungal species of genus, *Trichoderma* is considered a good bio-control agent that produces a variety of enzymes against *M. incognita*, and secrets plant growth-promoting compounds (Agrawal and Kotasthane 2012). *Trichoderma* spp. secret extracellular hydrolytic enzymes *viz*., serine protease (SprT), trypsin like proteas (PRA1) and chitinolytic (chi18-5 and chi18-12) that can parasitize nematode larva and eggs (Szabo et al. 2012). Comparative evaluation of protease enzyme expression in *T. harzianum* revealed that 13 peptidase encoding genes with the addition of aspartic protease genes P6281 and P9438, acidic serine protease gene PRA1, sedolisin protease gene P5216 and metalloendopeptidase gene P7455, all these genes play a major role in parasitising *M. incognita* eggs (Szabo et al. 2013). *Trichoderma* spp. were also involved in the release of some other nematicidal compounds like β-vinylcyclopentane-1α, 3α-diol, 6-pentyl-2H-pyran 2-one, trichodermin, and 4-(2-hydroxyethyl) phenol (Yang et al. 2012). However, the hatching of *Meloidogyne* spp. eggs were also inhibited by the cultural filtrates of *Trichoderma* isolates. This inhibition was directly proportional to the cultural filtrate concentration and the time of exposure (Rompalli et al. 2016).

Mechanisms of Action of Nematophagous Fungi Against *M. incognita*

The methods by which nematophagous fungi infects/kill root-knot nematode, *M. incognita* takes place by the process like attraction/recognition, adhesion, penetration and digestion through enzymatic action (Dong and Zhang 2006).

Attraction and Recognition of Nematodes

Attraction and recognition is the initial stage during the mechanism of nematodes infection by nematophagous fungi, during such process cell-cell communication and involvement of a range of interactions *viz*., physiological, biochemical or morphological taking place between fungi and *M. incognita*. The process of attraction and recognition were facilitated by certain volatile organic compounds (VOCs) secreted by the nematophagous fungi (Wang et al. 2010). Various VOCs include terpenoid (camphor), monoterpenes (α-pinene and β-pinene) released from the pine tree during the infection by pinewood nematode, *Bursaphelenchus xylophilus*. However, it has been found that endoparasitic fungus, *Esteya vermicola* mimics the scent of such VOCs that released from the pine tree infected by pinewood nematode (Lin et al. 2013). Although it has been found that nematode, *Neoaplectana glaseri* released a putative morphogenic signal (nemin) that induces trap formation in *A. conoides*, a compound ascaroside was also involved to induce of trap formation and adhesive network against nematodes in *A. oligospora* (Hsueh et al. 2013). According to Li et al. (2007), G proteins are the major proteins that act as sensors, inducing the pathogenesis, response to environmental signals and constricting-ring formation in *A. dactyloides*.

Adhesion to Nematodes Shell or Cuticle Through Adhesive Proteins

Adhesive proteins in nematophagous fungi are the polymer of extracellular fibrils and present on the spores or outer surface of traps of fungi and play major role for those fungi that adhered to the cuticle or shell of the root-knot nematode (Tunlid et al. 1991).

Lectins are considered as adhesive proteins that isolated from adhesive traps of nematophagous fungi, it functions as recognition of root-knot nematodes due to the presence of different glycosyls, like D-glucose, D-mannose and N-acetyl-D-galactosamine (GalNAc) (Nordbring-hertz and Mattiasson 1979). Balogh et al. (2003) noticed that deletion of a gene code for lectin protein (AOL_s00080g288) from *A. oligospora* did not affect its pathogenicity against PPNs. Two lectin genes (fucose-binding lectin gene and GalNAc-binding lectin gene) occurred in the nematophagous fungus, *D. stenobrocha* genome, enhancing the pathogenicity of fungus against PPNs (Liu et al. 2014). Few other genes that code for potent fungal adhesion protein are also occured in the nematophagous fungal genome along with lectins for example, 12, 17, and 26 CFEM containing proteins are found in *A. oligospora, D. stenobrocha*, and *D. haptotyla*, respectively (Meerupati et al. 2013). Similarly, the occurrence of 6, 6, and 28 GLEYA-containing proteins that function like lectins was also suggested by Meerupati et al. (2013). Quantitative Polymerase chain reaction analyses of 17 adhesion proteins in *A. oligospora* having five genes, AOL_s00076g567, AOL_s00043g50, AOL_s00007g5, AOL_s00210g231, and AOL_s00076g207 were changed or coded for trap formation mechanism in *A. oligospora* against *M. incognita* (Yang et al. 2011).

Enzymatic Action of Nematophagous Fungi Against *M. incognita*

Extracellular enzymes, such as collagenases, serine proteases, and chitinases, causes breaking of nematode eggshells and cuticles facilitating fungal penetration and colonization (Yang et al. 2013).

Collagen Degrading Enzyme (Collagenases) Such enzymes cause the degradation of collagen protein of nematodes. According to Tosi et al. (2002), almost all species under *Arthrobotrys* release collagenase enzymes. Other enzymes like glycoside hydrolases (GHs) are also played an important role in degradation of hemicellulose, cellulose, xylans, lignocellulose and other cellular constituents of PPNs including root-knot nematode (Gibson 2012).

Cuticle Degrading Protease (Serine Proteases) Serine proteases are the most studied extracellular enzymes released by nematophagous fungi. Approximately 20 serine proteases were identified from various nematophagous fungi in which P32 serine protease was first discovered from the fungus, *Pochonia rubescens* (*Verticillium suchlasporia*) (Yang et al. 2007b). The phylogenetic study suggested that serine protease belongs to two lineages, (I) neutral protease from nematode-trapping fungi, (II) alkaline proteases from nematode-parasitic fungi (Li et al. 2010). Both of the proteases differ in electrostatic surface potential distributions, the flexibility of substrate-binding sites and catalytic and nematicidal activities (Liang et al. 2011). Although pathogenicity of nematophagous fungus, *A. oligospora* against PPNs was improved by its genetic changes, i.e., by inserting an additional copy of cuticle-degrading protease (PII) into its genome (Ahman et al. 2002).

Chitin Degrading Enzymes (Chitinases) Egg shells of PPNs have a structural component known as chitin (40% w/w). Enzyme chitinases found in egg parasitic fungi were used to penetrate the egg shell of nematodes. The first chitinase Chi43 enzyme was isolated from two nematode eating fungi, *P. rubescens* and *P. chlamydosporia* (Tikhonov et al. 2002). Although 16 important genes that code for GH18 chitinases analysed from nematophagous fungi, *A. oligospora* and *D. stenobrocha* genomes respectively, provide nematicidal activities (Liu et al. 2014) (Fig. 5; Table 3).

Abiotic Approaches Against *M. incognita*

Various abiotic approaches were considered against *M. incognita* and farmers evaluated them to utilise as organics in their fields. Fortunately, they have been involved in controlling or keeping the PPNs population below the threshold level. Several researchers have reported the various organic products of plant origin, *viz*., botanicals, oil cakes, agriculture and industrial wastes have potent nematicidal and plant growth promoting properties after amending to the soil. Addition of these compounds to the soil enhance the releases of various metabolites from the plant such as alkaloids, terpenes, diterpenes, sesquiterpenes, fatty acid, glucosinolates, phenols and polyacetylenes which provide a defence to plants against pathogens including *M. incognita* (Thoden et al. 2011).

Mechanisms of Action of Various Organics Against *M. incognita*

Botanical Extracts Against *M. incognita* Plant extracts have nematicidal properties, and they reduce not only the population of nematodes, but also stimulate the growth of the plant (Olabiyi and Ayeni 2016). More than 100 species of plants have been utilized for their antinemic activities. Few of them showed promising results in killing root-knot nematodes *viz*., *Euphorbia caducifolia, Azadirachta indica, Calotropis procera* and *Nerium oleander*. They also exhibited inhibitory effects against J2s of root-knot nematodes (Laquale et al. 2015). According to Yuhui et al. (2018), crude root extract of *Fumaria parviflora* contains nematicidal compounds like alkaloids, sterol and alcohol. These compounds reduced root galls and killed J2s of *M. incognita* and alcoholic containing compounds from *F. parviflora* like 23α-Homostigmast-en-3β-ol, and Nonacosane-10-ol showed synergistic effects on J2s of *M. incognita* on tomato. Wen et al. (2019) tested *in vitro* aqueous extract of two plants *Paenoia rockii* and *Camellia oleifera* against *M. incognita*, extract of *P. rockii* at 5 mg/ml caused 100% mortality or inactivation of J2s of *M. incognita*. *In vivo* experiment by using aqueous extracts of chinaberry fruits (*Melia azedarach*), researchers got success in the management of *M. incognita* and *M. javanica* and improved soil biological activity (Ntalli et al. 2018). Aqueous extract of garlic contains compound allicin (diallyl thiosulfinate), tested *in vitro* against root-knot nematode, *M. incognita*. *In vitro* study of allicin showed inhibitory effect against *M. incognita*. However, *in vivo* study of allicin showed that it enhanced tomato yield and reduced the population of *M. incognita* by increasing enzymatic activities like peroxidase, catalase and superoxide dismutase in tomato leaves

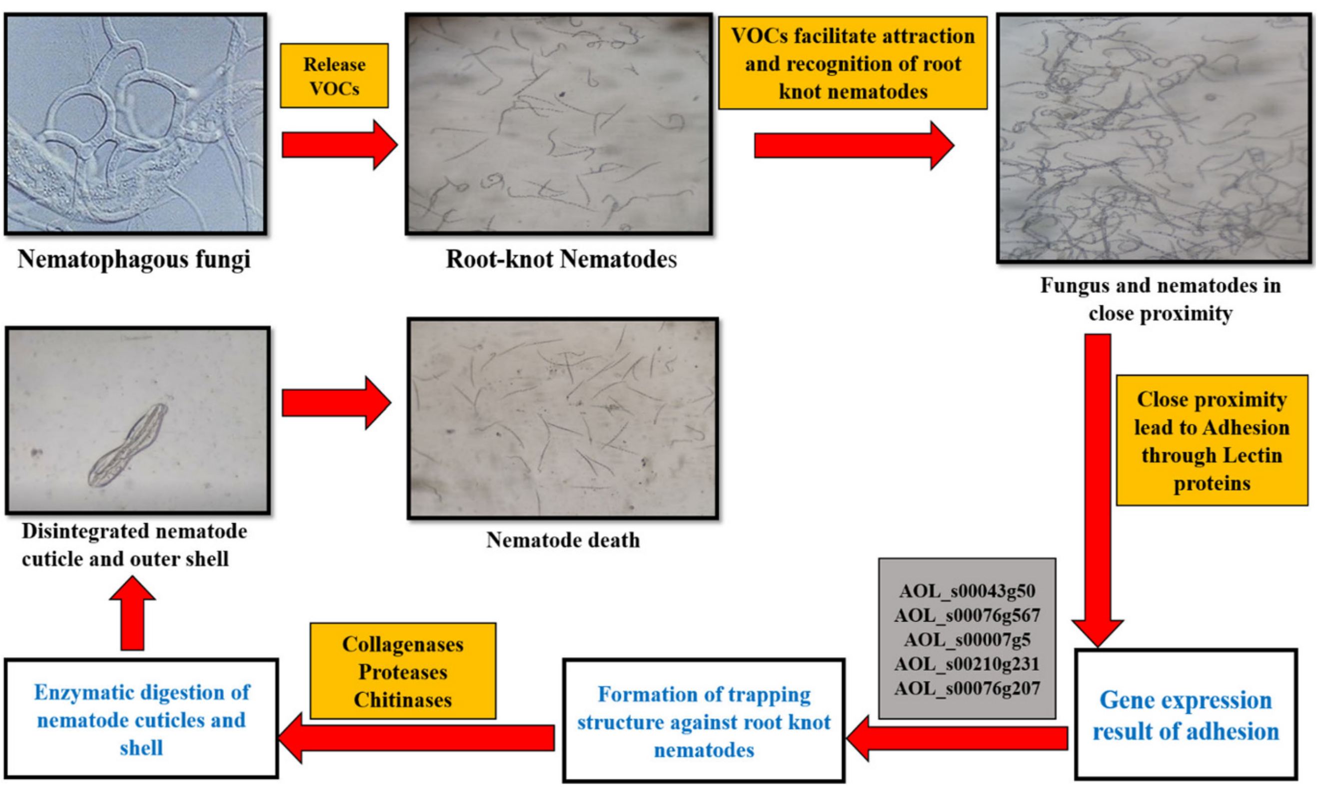

Fig. 5 Mechanisms of action of nematophagous fungi as bio agents against root-knot nematode, *M. incognita* in vegetable crops

Table 3 Application of biotic agents tested against various species of root-knot nematodes on vegetable crops

Fungal species	Root-knot nematode species	Vegetable crops	Type of study	References
Trichoderma longibrachiatum	*Meloidogyne incognita*	Cucumber	*In vitro, in vivo*	Zhang et al. (2015)
Lecanicillium muscarium	*Meloidogyne incognita*	Tomato	*In vitro, in vivo*	Hussain et al. (2018)
Trichoderma viridae *Trichoderma herzianum*	*Meloidogyne incognita*	Tomato	*In vivo*	Mukhtar (2018)
Penicillium chrysogenum	*Meloidogyne incognita*	Cucumber	*In vivo*	Sikandar et al. (2019)
Arthrobotrys oligospora	*Meloidogyne incognita*	Tomato	*In vitro, in vivo*	Soliman et al. (2021)
Purpureocillium lilacinum	*Meloidogyune incognita*	Tomato	*In vivo*	Hore et al. (2018)
Paecilomyces lilacinus	*Meloidogyne incognita*	Egg plant	*In vivo*	Nisha and Sheela (2016)
Trichoderma harzianum	*Meloidogyne incognita*	Pea	*In vivo*	Brahma and Borah (2016)
Penicillium crysogenum *Pochonia chlamydosporia*	*Meloidogyne incognita*	Cucumber	*In vitro, in vivo*	Naz et al. (2021)
Trichoderma spp	*Meloidogyne incognita*	Pepper	*In vivo*	Herrera-Parra et al. (2017)
Pochonia chlamydosporia	*Meloidogyne incognita* *Meloidogyne enterolobii*	Tomato/ Banana	*In vitro, in vivo*	Silva et al. (2017)
Xylaria grammica	*Meloidogyne incognita*	Tomato/ Melon	*In vitro, in vivo*	Kim et al. (2018)
Pochonia chlamydosporia	*Meloidogyne incognita*	Carrot	*In vivo*	Bontempo et al. (2017)
Paecilomyces lilacinus	*Meloidogyne javanica*	Tomato	*In vivo*	Hanawi (2016)

compared to untreated control (Ji et al. 2019). Thus, allicin may be a potent alternative of chemical nematicides for the management of root-knot nematodes. Water extracts of fruits and leaves of *Coccinia grandis* and *Ageratum conyzoides* showed the mortality of J2s and inhibition of egg hatchability of *M. incognita in vitro* (Asif et al. 2017). According to Ntalli et al. (2020), lemon thyme powder (*Thymus Citriodorus*) enhanced the growth of tomato plants in a dose-response manner. When it was applied in the soil at 1 g kg^{-1}, it exhibited nematicidal activity at a 95% level on *M. incognita*. D'Addabbo et al. (2020) tested *in vitro* aqueous extract of *Medicago* spp. (*M. hybrid, M. murex, M. heyniana, M. lupulina*, and *M. truncatula*) which have bioactive compounds, saponins that killed the J2s and inhibited egg hatching of *M. incognita*.

Plant Oil Cakes Against *M. incognita* Oil cakes are an effective source of phosphorus, nitrogen and potassium (NPK) that improve the chemical, physical and biological activity of soil and inhibit the development of root-knot nematodes. Soil amended with different types of oil cakes which took about 10–14 days for decomposition after that releases nutrients for plant growth and eventually caused inhibition of the population of PPNs. Amendment of oil cakes in moist soil is more effective compared to dry soil. Amendment of mustard and neem cake into the soil was found to be effective against the multiplication of root-knot nematode. However, oil cakes from *Jatropha* sp. flax (*Linum usitatisimum*), mahua (*Madhoca indica*), sesame (*Sesamum indicum*), castor (*Ricinum communis*) and groundnut (*Arachis hypogea*) have been found effective in reducing the multiplication of root-knot nematodes (Rehman et al. 2015). Neem cake reduced the egg hatching, killing *M. incognita* J2s and also enhanced tomato growth and yield (Kumar and Khanna 2008). The application of neem cake effectively suppressed root-knot nematode, and increased the growth and yield parameters of cucumber (Devi and Das 2016).

Agriculture and Industrial Wastes Against *M. incognita* Agricultural wastes can be characterised as plant parts or pieces that remain in the field after crop harvesting. These wastes may vary in their decomposition rate or properties like antinemic (Lal 2005). It improves soil's chemical, physical and biological properties and manages root-knot nematodes after their proper and complete decomposition. Application of agricultural wastes like saw dust and rice husk into the soil inhibited the population of root-knot nematodes (*Meloidogyne* spp.) and enhanced growth and yield of tomato crop (Prakash and Singh 2014). Due to global industrialization and mass crop cultivation, it is important to invent a new method or process for changing industrial wastes into value-added products that could be utilized in controlling soil-borne pathogens like root-knot nematodes. Brito et al. (2020) were considering some agro-industrial waste *viz*., sugarcane bagasse, orange bagasse, poultry litter, and some other wastes to manage *M. javanica* in pots. Several wastes like soybean hulls, orange bagasse and others are most efficient in the control of root-knot nematodes up to 55–100%. Cassava (*Manihot esculenta*), starch industry releases a liquid residue known as Manipueira as good source of cyanogenic glycosides. It showed nematicidal

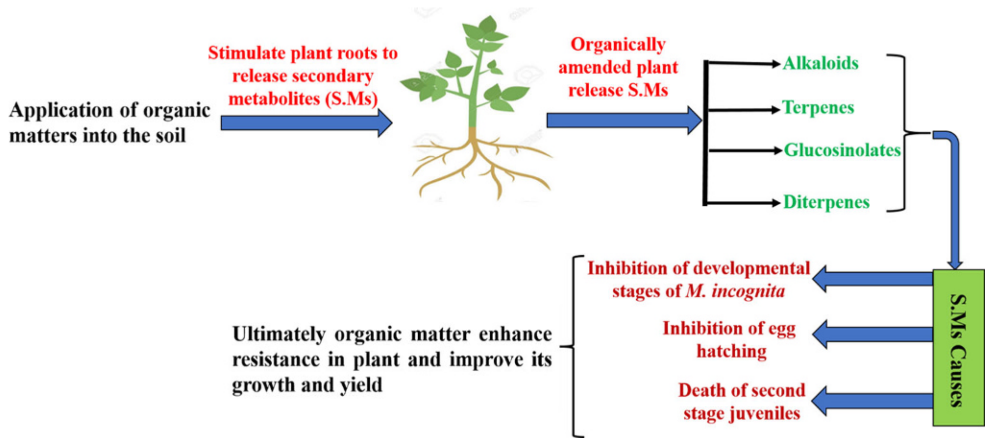

Fig. 6 Mechanisms of action of organic matter against root-knot nematode, *M. incognita*

Table 4 Application of abiotic agents tested against various species of root-knot nematodes on vegetable crops

Type of abiotic substances	Root-knot nematode species	Vegetable crops	Type of study	References
Root extract of *Fumaria parviflora*	*Meloidogyne incognita*	Tomato	*In vitro, in vivo*	Yuhui et al. (2018)
Aquas extract of Peganum (Peganum harmala L.)	*Meloidogyne incognita*	Egg plant	*In vivo*	Bakr and Ketta (2018)
Aquas extract from fruits of *Melia azedarach*	*Meloidogyne incognita*, *Meloidogyne javanica*	Tomato	*In vivo*	Ntalli et al. (2018)
Essential oil from garlic	*Meloidogyne incognita*	Tomato	*In vitro, in vivo*	Jardim et al. (2020)
Leaves of *Phyllanthus amarus*	*Meloidogyne incognita*	Carrot	*In vitro, in vivo*	Khan et al. (2019)
Green manure from *Fumaria parviflora*	*Meloidogyne incognita*	Tomato	*In vivo*	Naz et al. (2015)
Extract of Aloe vera	*Meloidogyne incognita*	Tomato	*In vivo*	Abdulrahman et al. (2019)
Lemon thyme powder	*Meloidogyne incognita*	Tomato	*In vivo*	Ntalli et al. (2020)
Chopped fresh leaves of neem and madar	*Meloidogyne incognita*	Bottle gourd	*In vivo*	Singh and Patel (2015)
Manipueira industrial waste	*Meloidogyne incognita*	Tomato	*In vivo*	Nasu et al. (2015)
Castor cake	*Meloidogyne incognita*	Okra	*In vivo*	Archana and Goswami (2017)
Essential oil from *Dysphania ambrosioides*	*Meloidogyne incognita*	Tomato	*In vitro, in vivo*	Barros et al. (2019a)
Neem leaf powder	*Meloidogyne* spp	Chilli pepper	*In vivo*	Kankam and Sowley (2016)
Neem cake	*Meloidogyne incognita*	Cucumber	*In vivo*	Devi and Das (2016)
Sisal liquid residue industrial waste	*Meloidogyne javanica*	Tomato	*In vitro, in vivo*	Damasceno et al. (2015)
Neem, karanj and mustard cake	*Meloidogyne incognita*	Okra	*In vivo*	Baheti et al. (2019)
Aquas sesame seed extract	*Meloidogyne spp*	Okra	*In vivo*	Kankam et al. (2015)
Essential oil from *Piptadenia viridiflora*	*Meloidogyne incognita*	Tomato	*In vitro, in vivo*	Barros et al. (2019b)
Essential oil from *Artemisia nilagrica*	*Meloidogyne incognita*	Tomato	*In vivo*	Kalaiselvi et al. (2019)

effects against *M. incognita* by reducing galls or killing J2s and improved tomato yield (Nasu et al. 2015).

Essential Oils (EOs) Against *M. incognita* Researchers and industrialist engage in the evaluation of essential oils (EOs) as bio-nematicides for the root-knot nematodes. EOs and other secondary metabolites extracted from plants were directly affected the root-knot nematodes, especially on the J2s and egg hatchability (El-Nagdi et al. 2017). *In vitro* testing of EOs from true myrtle (*Myrtus communis*) showed nematicidal activity against *M. incognita* (Ardakani et al. 2013). According to Onkendi et al. (2014), EOs from plants belonging to the family Asteraceae were utilized as management for root-knot nematodes. *In vitro* experiment showed that EOs were considered as soil bio fumigants for reducing galls or killing *M. incognita* J2s on tomato and enhancing its yield (Laquale et al. 2015). EOs from Mexican tea (*Dysphania ambrosioides*) have 99.08% of total oil with nematicidal activities, i.e., inhibited egg hatching by 100% and galls by 99.5%, further chromatography, mass spectrometry studies showed that oil from *D. ambrosioides* was composed of *p*-cymene (3.35%), (Z)-ascaridole (87.28%) and E-ascaridole (8.45%). EOs from three Brazilian plants (*Hyptis suaveolens, Astronium graveolens* and *Piptadenia viridiflora*) were tested both *in vitro* and *in vivo* against *M. incognita*. Among them, *Piptadenia viridiflora* showed inhibitory effect against *M. incognita* due to the presence of major component, benzaldehyde. These component was able to inhibit egg hatching up to 65% and its oxime compounds were able to reduce galls up to 84% and egg hatching up to 89% on tomato plant (Barros et al. 2019b) (Fig. 6; Table 4).

Conclusion

When examining the significance of monetary damage due to root-knot nematode, *M. incognita* and the fact of the limitations by the government for the utilization of pesticides, it is important to researchers that there is a demand for the evolving new novel eco-friendly approaches against *M. incognita*. Several scientists are concerned about the excessive utilization of pesticides for controlling the crop pests by the farmers, and they pressurize the farmers to minimize the use of pesticides to overcome the environment pollution issues. This review mainly focused on the bio-organic management as eco-friendly for controlling of *M. incognita*. Biological agents and organic matters are the alternative for pesticides that do not only manage *M. incognita* as eco-friendly, but also improve growth and yield of vegetables. In biological agents, nematophagous fungi manage root-knot nematodes by cuticle penetration, absorption and digestion of nematode cuticle and AM fungi colonizes the rhizosphere, induced resistance in plants and compete with nematode and killing them. Organic soil amendments prompt the development of beneficial soil microbe's population and reduce the population of nematodes or plant diseases as well as boost soil fertility, water holding capacity, physical properties of soil, and plant growth. Both soil amendments and the bio-control agents have been studied to some extent against root-knot nematodes. Still, with advancements in technology recently, there should be more profound studies on how these two approaches can synergistically affect nematodes and kill them. Whatever methods/strategies are invented, in future the focus is on the essential aspects like green approaches which manage root-knot nematodes without affecting environment and human health.

Acknowledgements The authors are highly obliged to the Head of Department (Botany), Aligarh Muslim University, Aligarh, India for giving valuable suggestion regarding to the work.

Author Contribution AK suggested the idea of the manuscript. AK, GA and MH find out the literature and wrote the complete manuscript. AAK has done the final editing of the manuscript. AK and MH compile and formatted the manuscript according to journal guidelines. AK is responsible for the correspondence of manuscript. The manuscript has been read and approved by all the authors.

Conflict of interest A. Khan, G. Ahmad, M. Haris and A.A. Khan declare that they have no competing interests.

References

Abdulrahman O, Titilayo AM, Alhaji IA, Mamani JN, Onyekachi EE (2019) Nematicidal Activity of Aloe vera Extract/Exudates on Root-knot Nematodes (M. incognita) Associated with Tomato (Lycopersicun esculentum) Plant Growth Parameters. South Asian Journal of Parasitology, 2(4):1–5.

Agrawal T, Kotasthane AS (2012) Chitinolytic assay of indigenous Trichoderma isolates collected from different geographical locations of Chhattisgarh in Central India. Springer Plus 1(1):1–10. https://doi.org/10.1186/2193-1801-1-73

Ahmad G, Khan A, Khan AA, Ali A, Mohhamad HI (2021) Biological control: a novel strategy for the control of the plant parasitic nematodes. Antonie Van Leeuwenhoek. https://doi.org/10.1007/s10482-021-01577-9

Ahman J, Johansson T, Olsson M, Punt PJ, van den Hondel CA, Tunlid A (2002) Improving the pathogenicity of a nematode-trapping fungus by genetic engineering of a subtilisin with nematotoxic activity. Appl Environ Microbiol 68(7):3408–3415. https://doi.org/10.1128/AEM.68.7.3408-3415.2002

Alban R, Guerrero R, Toro M (2013) Interactions between a root knot nematode (Meloidogyne exigua) and arbuscular mycorrhizae in coffee plant development (Coffea arabica). Am J Plant Sci 4(7A2):19–23. https://doi.org/10.4236/ajps.2013.47A2003

Archana S, Goswami BK (2017) Performance of leaves and their respective oil seed cakes on plant growth parameters and soil population of root knot nematode on okra. Plant Arch 17(2):1055–1057

Ardakani AS, Hosyninejad SA, Pourshirzad A (2013) Killing effects of Myrtus communis L. essential oil on Meloidogyne incognita Research article. Int J Agric Crop Sci 5(8):806–810

Asif M, Tariq M, Khan A, Siddiqui MA (2017) Biocidal and antinemic properties of aqueous extracts of Ageratum and Coccinia against root-knot nematode, Meloidogyne incognita in vitro. J Agric Sci 12(2):108–123. https://doi.org/10.4038/jas.v12i2.8229

Baheti BL, Bhati SS, Singh H (2019) Efficacy of different oil-cakes as soil amendment for the management of root-knot nematode, meloidogyne incognita infecting okra (Abelmoschus esculentus L.). Int J Curr Microbiol App Sci 8(12):799–808

Bakr RA, Ketta HA (2018) Nematicidal potential of some botanical products against Meloidogyne incognita infecting eggplant. Ind J Nematol 48(2):203–211

Balogh J, Tunlid A, Rosen S (2003) Deletion of a lectin gene does not affect the phenotype of the nematode-trapping fungus Arthrobotrys oligospora. Fungal Genet Biol 39:128–135

Barros AF, Campos VP, De Oliveira DF, De Jesus SF, Jardim IN, Costa VA, Silva GH (2019b) Activities of essential oils from three Brazilian plants and benzaldehyde analogues against Meloidogyne incognita. Nematology 21:1081–1089. https://doi.org/10.1163/15685411-00003276

Barros AF, Campos VP, de Paula LL, Oliveira DF, de Silva FJ, Terra WC, Salimena JP (2019a) Nematicidal screening of essential oils and potent toxicity of Dysphania ambrosioides essential oil against Meloidogyne incognita in vitro and in vivo. J Phytopathol 167(7–8):380–389. https://doi.org/10.1111/jph.12803

Basumatary B, Mahanta B, Borah A, Dutta P (2018) Assessment of yield losses due to Meloidogyne incognita on ivy gourd (Coccinea indica L.). Ind J Nematol 48(1):119–121

Baum C, El-Tohamy W, Gruda N (2015) Increasing the productivity and product quality of vegetable crops using arbuscular mycorrhizal fungi: a review. Sci Hortic 187:131–141. https://doi.org/10.1016/j.scienta.2015.03.002

Bell CA, Lilley CJ, McCarthy J, Atkinson HJ, Urwin PE (2019) Plant-parasitic nematodes respond to root exudate signals with host-specific gene expression patterns. PLoS Pathog 15:1–19. https://doi.org/10.1371/journal.ppat.1007503

Bhati SSB, Baheti BL (2021) Estimation of avoidable losses caused by Meloidogyne incognita infecting cucumber in poly-house. J Agric Appl Biol 2(1):35–40. https://doi.org/10.11594/jaab.02.01.05

Bontempo AF, Lopes EA, Fernandes RH, Freitas LGD, Dallemole-Giaretta R (2017) Dose-response effect of Pochonia chlamydosporia against Meloidogyne incognita on carrot under field conditions. Rev Caatinga 30(1):258–262

Brahma U, Borah A (2016) Management of Meloidogyne incognita on pea with bioagents and organic amendment. Ind J Nematol 46(1):58–61

Brito OD, Ferreira JC, Hernandes I, da Silva EJ, Dias-Arieira CR (2020) Management of Meloidogyne javanica on tomato using agro-industrial wastes. Nematology 22(10):1141–1154

Cayrol JC, Castet R, Samson RA (1986) Comparative activity of different Hirsutella species towards three plant parasitic nematodes. Rev Nematol 9(4):412–414

Chan YL, He Y, Hsiao TT, Wang CJ, Tian Z, Yeh KW (2015) Pyramiding taro cystatin and fungal chitinase genes driven by a synthetic promoter enhances resistance in tomato to root-knot nematode Meloidogyne incognita. Plant Sci 231:74–81

Chandra P, Sao R, Gautam SK, Poddar AN (2010) Initial population density and its effect on the pathogenic potential and population growth of the root knot nematode Meloidogyne incognita in four species of cucurbits. Asian J Plant Pathol 4(1):1–15

Chariou PL, Steinmetz NF (2017) Delivery of pesticides to plant parasitic nematodes using tobacco mild green mosaic virus as a Nano carrier. ACS Nano 11(5):4719–4730

Collange B, Navarrete M, Peyre G, Mateille T, Tchamitchian M (2011) Root-knot nematode (Meloidogyne) management in vegetable crop production: the challenge of an agronomic system analysis. Crop Prot 30:1251–1262

Cooke RC (1962) The ecology of nematode-trapping fungi in the soil. Ann Appl Biol 50(3):507–513

Curtis R, Robinson A, Perry R (2009) Hatch and host location. In: Perry RN, Moens M, Starr JL (eds) Root- knot nematodes. CAB International, Wallingford, pp 139–162

D'Addabbo T, Argentieri MP, Żuchowski J, Biazzi E, Tava A, Oleszek W (2020) Activity of saponins from Medicago species against phytoparasitic nematodes. Plants 9:1–19. https://doi.org/10.3390/plants9040443

Damasceno JC, Soares AC, Jesus FN, Sant'Ana RS (2015) Sisal leaf decortication liquid residue for controlling Meloidogyne javanica in tomato plants. Hortic Bras 33:155–162. https://doi.org/10.1590/s0102-053620150000200004

Darekar KS, Mhase NL (1988) Assessment of yield losses due to root-knot nematode Meloidogyne incognita race 3 in tomato, brinjal and bittergourd. International nematology network newsletter

Davis EL, Haegeman A, Kikuchi T (2011) Degradation of the plant cell wall by nematodes. In: Genomics and molecular genetics of plant-nematode interactions. Springer, Dordrecht, pp 255–272

De la Peña E, Echeverría SR, Putten WH, Van Der Freitas H, Moens M (2006) Mechanism of control of root-feeding nematodes by mycorrhizal fungi in the dune grass Ammophila arenaria. New Phytol 169:829–840. https://doi.org/10.1111/j.1469-8137.2005.01602

Decraemer W, Hunt DJ (2013) Structure and classification. In: Perry RN, Moens M (eds) Plant Nematology, 2nd edn. CABI, Wallingford, pp 3–39

Den Akker SE, Birch PR (2016) Opening the effector protein toolbox for plant-parasitic cyst nematode interactions. Mol Plant 9(11):1451. https://doi.org/10.1016/j.molp.2016.09.008

Devi S, Das D (2016) Effect of organic amendments on root-knot nematode, Meloidogyne incognita in cucumber. Pest Manag Hortic Ecosyst 22(2):176–181

Dong LQ, Zhang KQ (2006) Microbial control of plant-parasitic nematodes: a five-party interaction. Plant Soil 288(1):31–45

Druzhinina IS, Seidl-Seiboth V, Herrera-Estrella A, Horwitz BA, Kenerley CM, Monte E, Kubicek CP (2011) Trichoderma: the genomics of opportunistic success. Nat Rev Microbiol 9(10):749–759

Duddington CL (1962) Predacious fungi and the control of eelworms. Viewpoints Biol 1:151–200

El-Nagdi WMA, Youssef MMA, El-Ghonaimy AM (2017) Efficacy of some bio products and plant defence elicitors against root-knot nematode, Meloidogyne incognita infesting dry common bean, Phaseolus vulgaris. Sci Agric 18(2):38–44

Elsen A, Baimey H, Swennen R, De Waele D (2003a) Relative mycorrhizal dependency and mycorrhiza nematode interaction in banana cultivars (Musa spp.) differing in nematode susceptibiliy. Plant Soil 256(2):303–313. https://doi.org/10.1023/A:1026150917522

Elsen A, Beeterens R, Swennen R, De Waele D (2003b) Effects of an arbuscular mycorrhizal fungus and two plant-parasitic nematodes on Musa genotypes differing in root morphology. Biol Fertil Soils 38:367–376. https://doi.org/10.1007/s00374-003-0669-3

Escobar C, Barcala M, Cabrera J, Fenoll C (2015) Overview of root-knot nematodes and giant cells. Adv Bot Res 73:1–32

Fan JW, Hu CL, Zhang LN, Li ZL, Zhao FK, Wang SH (2015) Jasmonic acid mediates tomato's response to root knot nematodes. J Plant Growth Regul 34(1):196–205

Fiorilli V, Catoni M, Francia D, Cardinale F, Lanfranco L (2011) The arbuscular mycorrhizal symbiosis reduces disease severity in tomato plants infectedby Botrytis cinerea. J Plant Pathol 93:237–242.

Forghani F, Hajihassani A (2020) Recent advances in the development of environmentally benign treatments to control root-knot nematodes. Front Plant Sci. 11:1125. https://doi.org/10.3389/fpls.2020.01125

Fujimoto T, Tomitaka Y, Abe H, Tsuda S, Futai K, Mizukubo T (2011) Jasmonic acid signaling pathway of Arabidopsis thaliana is important for root-knot nematode invasion. Nematol Res 41:9–17

Gao H, Qi G, Yin R, Zhang H, Li C, Zhao X (2016) Bacillus cereus strain S2 shows high nematicidal activity against Meloidogyne incognita by producing sphingosine. Sci Rep 6(1):1–11

Gao X, Starr J, Göbel C, Engelberth J, Feussner I, Tumlinson J, Kolomiets M (2008) Maize 9-lipoxygenase ZmLOX3 controls development, root-specific expression of defence genes, and resistance to root-knot nematodes. Mol Plant Microbe Interactions 21(1):98–109

Ghule TM, Singh A, Khan MR (2014) Root knot nematodes: threat to Indian agriculture. Pop Kheti 2(3):126–130

Gibson LJ (2012) The hierarchical structure and mechanics of plant materials. J R Soc Interface 9(76):2749–2766

Glick BR (2012) Plant growth-promoting bacteria: mechanisms and applications. Scientifica 2012

Gowda TM, Rai AB, Singh B (2017) Technical bulletin No. 76. IIVR, Varanasi, p 32

Gutjahr C, Paszkowski U (2013) Multiple control levels of root system remodeling in arbuscular mycorrhizal symbiosis. Front Plant Sci 4:204

Hajihassani A, Rutter WB, Schwarz T, Woldemeskel M, Ali ME, Hamidi N (2019) Characterization of resistance to major tropical root-knot nematodes (Meloidogyne spp.) in Solanum sisymbrifolium. Phytopathology 110:666–673. https://doi.org/10.1094/PHYTO-10-19-0393-R

Hallmann J, Davies KG, Sikora R (2009) Biological Control Using Microbial Pathogens, Endophytes and Antagonist. In: Root-knot nematodes, p 380

Hanawi MJ (2016) Tagetes erecta with native isolates of Paecilomyces lilacinus and Trichoderma hamatum in controlling root-knot nematode Meloidogyne javanica on tomato. Int J Appl Innovation Eng Manage 5(1):81–88

Herrera-Parra E, Cristóbal-Alejo J, Ramos-Zapata JA (2017) Trichoderma strains as growth promoters in Capsicum annuum and as biocontrol agents in Meloidogyne incognita. Chil J Agric Res 77(4):318–324

Hore J, Roy K, Maiti AK (2018) Evaluation of Bio-Nematon (Purpureocillium lilacinum 1.15% WP) against root-knot nematode (Meloidogyne incognita) in tomato. J Entomol Zool Stud 6(4):1700–1704

Hsueh YP, Mahanti P, Schroeder FC, Sternberg PW (2013) Nematode-trapping fungi eavesdrop on nematode pheromones. Curr Biol 23(1):83–86

Hunt DJ, Handoo ZA (2009) Taxonomy, identification and principal species. In: Perry RN, Moens M, Starr JL (eds) Root-knot Nematodes. Cap. 3. CAB International, Wallingford, pp 55–88

Hussain M, Zouhar M, Rysanek P (2018) Suppression of Meloidogyne incognita by the entomopathogenic fungus Lecanicillium muscarium. Plant Dis 102(5):977–982

Jain RK, Mathur KN, Singh RV (2007) Estimation of losses due to plant parasitic nematodes on different crops in India. Ind J Nematol 37(2):219–221

Jamal Q, Cho JY, Moon JH, Munir S, Anees M, Kim KY (2017) Identification for the First Time of Cyclo (d-Pro-l-Leu) Produced by Bacillus amyloliquefaciens Y1 as a Nematocide for Control of Meloidogyne incognita. Molecules 22(11):1839

Jardim IN, Oliveira DF, Campos VP, Silva GH, Souza PE (2020) Garlic essential oil reduces the population of Meloidogyne incognita in tomato plants. Eur J Plant Pathol 157(1):197–209

Ji X, Li J, Meng Z, Dong S, Zhang S, Qiao K (2019) Inhibitory effect of allicin against Meloidogyne incognita and Botrytis cinerea in tomato. Sci Hortic 253:203–208

Jones JD, Dangl JL (2006) The plant immune system. Nature 444(7117):323–329

Jones JT, Haegeman A, Danchin EG, Gaur HS, Helder J, Jones MG, Perry RN (2013) Top 10 plant-parasitic nematodes in molecular plant pathology. Mol Plant Pathol 14(9):946–961

Jung SC, Martinez-Medina A, Lopez-Raez JA, Pozo MJ (2012) Mycorrhiza-induced resistance and priming of plant defenses. J Chem Ecol 38(6):651–664

Kalaiselvi D, Mohankumar A, Shanmugam G, Thiruppathi G, Nivitha S, Sundararaj P (2019) Altitude-related changes in the phytochemical profile of essential oils extracted from Artemisia nilagirica and their nematicidal activity against Meloidogyne incognita. Ind Crops Prod 139:111472. https://doi.org/10.1016/j.indcrop.2019.111472

Kankam F, Sowley ENK (2016) Evaluation of neem (Azadirachta indica L.) products for the control of root-knot nematode of chilli pepper (Capsicum annum L.). Arch Phytopathol Plant Prot 49(5–6):111–119

Kankam F, Sowley ENK, Mohammed A (2015) Management of root-knot nematode (Meloidogyne spp.) on okra (Abelmoschus esculentus L. Moench) with aqueous sesame seed extract. Int J Agron Agric Res 6(4):24–31

Kaskavalci G (2007) Effects of soil solarization and organic amendment treatments for controlling Meloidogyne incognita in tomato cultivars in Western Anatolia. Turk J Agric For 31(3):159–167

Kenney E, Eleftherianos I (2016) Entomopathogenic and plant pathogenic nematodes as opposing forces in agriculture. Int J Parasitol 46(1):13–19

Kerry BR, Hominick WM (2002) Biological control. In: Lee DL (ed) The biology of nematodes. Taylor & Francis, London

Khan MR (2008) Current options for managing nematodes pest of crops in India. Department of Agricultural Entomology, West Bengal

Khan F, Asif M, Khan A, Tariq M, Ansari T, Shariq M, Siddiqui MA (2019) Evaluation of the nematicidal potential of some botanicals against root-knot nematode, Meloidogyne incognita infected carrot: In vitro and greenhouse study. Curr Plant Biol 20:100115. https://doi.org/10.1016/j.cpb.2019.100115

Kim TY, Jang JY, Yu NH, Chi WJ, Bae CH, Yeo JH, Kim JC (2018) Nematicidal activity of grammicin produced by Xylaria grammica KCTC 13121BP against Meloidogyne incognita. Pest Manag Sci 74(2):384–391. https://doi.org/10.1002/ps.4717

Koffi MC, Vos C, Draye X, Declerck S (2013) Effects of Rhizophagus irregularis MUCL 41833 on the reproduction of Radopholus similis in banana plantlets grown under in vitro culture conditions. Mycorrhiza 23(4):279–288

Kumar S, Khanna AS (2008) Role of Trichoderma harzianum and neem cake separately and in combination against root-knot nematode on tomato. Ind J Nematol 38:264–266

Lal R (2005) Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. Land Degrad Dev 17:197–209

Laquale S, Candido V, Avato P, Argentieri MP, d'Addabbo T (2015) Essential oils as soil biofumigants for the control of the root-knot nematode Meloidogyne incognita on tomato. Ann Appl Biol 167(2):217–224

Lee YS, Kim KY (2016) Antagonistic potential of Bacillus pumilus L1 against root-Knot nematode, Meloidogyne arenaria. J Phytopathol 164(1):29–39

Li G, Zhang K, Xu J, Dong J, Liu Y (2007) Nematicidal substances from fungi. Recent Pat Biotechnol 1:212–233

Li HY, Yang GD, Shu HR, Yang YT, Ye BX, Nishida I, Zheng CC (2006) Colonization by the arbuscular mycorrhizal fungus Glomus versiforme induces a defense response against the root-knot nematode Meloidogyne incognita in the grapevine (Vitis amurensis Rupr.), which includes transcriptional activation of the class III chitinase gene VCH3. Plant Cell Physiol 47(1):154–163

Li J, Yu L, Yang J, Dong L, Tian B, Yu Z, Zhang K (2010) New insights into the evolution of subtilisin-like serine protease genes in Pezizomycotina. BMC Evol Biol 10(1):1–14

Li J, Zou C, Xu J, Ji X, Niu X, Yang J, Huang X, Zhang KQ (2015) Molecular mechanisms of nematode-nematophagous microbe interactions: basis for biological control of plant-parasitic nematodes. Annu Rev Phytopathol 53:67–95

Liang L, Liu S, Yang J, Meng Z, Lei L, Zhang K (2011) Comparison of homology models and crystal structures of cuticle-degrading proteases from nematophagous fungi: structural basis of nematicidal activity. FASEB J 25(6):1894–1902

Lin F, Ye J, Wang H, Zhang A, Zhao B (2013) Host deception: predaceous fungus, Esteya vermicola, entices pine wood nematode by mimicking the scent of pine tree for nutrient. Plos One 8(8):71676

Lioussanne L (2010) The role of the arbuscular mycorrhiza-associated rhizobacteria in the biocontrol of soilborne phytopathogens. Span J Agric Res 8(S1):S51–S61

Liu K, Zhang W, Lai Y, Xiang M, Wang X, Zhang X, Liu X (2014) Drechslerella stenobrocha genome illustrates the mechanism of constricting rings and the origin of nematode predation in fungi. BMC Genom 15(1):1–14

Lopez-Llorca LV, Macia-Vicente JG, Jansson HB (2008) Mode of action and interactions of nematophagous fungi. In: Integrated management and biocontrol of vegetable and grain crops nematodes. Springer, Dordrecht, pp 51–76

Lunt DH, Kumar S, Koutsovoulos G, Blaxter ML (2014) The complex hybrid origins of the root knot nematodes revealed through comparative genomics. Peer J 2:e356

Luo H, Mo M, Huang X, Li X, Zhang K (2004) Coprinus comatus: a basidiomycete fungus forms novel spiny structures and infects nematode. Mycologia 96(6):1218–1224

Meerupati T, Andersson KM, Friman E, Kumar D, Tunlid A, Ahren D (2013) Genomic mechanisms accounting for the adaptation to parasitism in nematode-trapping fungi. PLoS Genet 9(11):e1003909

Miransari M (2011) Interactions between arbuscular mycorrhizal fungi and soil bacteria. Appl Microbiol Biotechnol 89(4):917–930

Molinari S, Leonetti P (2019) Bio-control agents activate plant immune response and prime susceptible tomato against root-knot nematodes. Plos One 14(12):e213230

Moosavi MR, Zare R (2012) Fungi as biological control agents of plant-parasitic nematodes. In: Merillon JM, Ramawat KG (eds) Plant Defence: Biological Control. Springer, Dordrecht, pp 67–107

Mukhtar T (2018) Management of root-knot nematode, Meloidogyne incognita, in tomato with two Trichoderma species. Pak J Zool. https://doi.org/10.17582/journal.pjz/2018.50.4.sc15

Nasu ÉDGC, Formentini HM, Furlanetto C (2015) Effect of manipueira on tomato plants infected by the nematode Meloidogyne incognita. Crop Prot 78:193–197. https://doi.org/10.1016/j.cropro.2015.08.005

Naz I, Khan RAA, Masood T, Baig A, Siddique I, Haq S (2021) Biological control of root knot nematode, Meloidogyne incognita, in vitro, greenhouse and field in cucumber. Biol Control 152:104429. https://doi.org/10.1016/j.biocontrol.2020.104429

Naz I, Saifullah, Palomares-Rius JE, Khan SM, Ali S, Ahmad M, Ali A, Khan A (2015) Control of southern root knot nematode Meloidogyne incognita (Kofoid and White) Chitwood on tomato using green manure of Fumaria parviflora Lam (Fumariaceae). Crop Prot 67:121–129. https://doi.org/10.1016/j.cropro.2014.10.005

Nisha MS, Sheela MS (2016) Effect of fungal egg parasite, Paecilomyces lilacinus (Thom.) Samson on Meloidogyne incognita in brinjal. Ind J Nematol 46:157–159

Nordbring-Hertz B, Mattiasson B (1979) Action of a nematode-trapping fungus shows lectin-mediated host-microorganism interaction. Nature 281:477–479

Ntalli N, Bratidou Parlapani A, Tzani K, Samara M, Boutsis G, Dimou M, Monokrousos N (2020) Thymus citriodorus (Schreb) botanical products as eco-friendly nematicides with bio-fertilizing properties. Plants 9(2):202

Ntalli N, Monokrousos N, Rumbos C, Kontea D, Zioga D, Argyropoulou MD, Tsiropoulos NG (2018) Greenhouse bio fumigation with Melia azedarach controls Meloidogyne spp. and enhances soil biological activity. J Pest Sci 91(1):29–40

Nuccio EE, Hodge A, Pett-Ridge J, Herman DJ, Weber PK, Firestone MK (2013) An arbuscular mycorrhizal fungus significantly modifies the soil bacterial community and nitrogen cycling during litter decomposition. Environ Microbiol 15(6):1870–1881

Olabiyi TI, Ayeni BP (2016) Assessment of Azadirachta indica and Cleome viscosa liquid-formulations as bio-nematicides in the management of nematode pests of okra. Afr J Agric Res 11(6):467–471

Onkendi EM, Kariuki GM, Marais M, Moleleki LN (2014) The threat of root-knot nematodes (Meloidogyne spp.) in Africa: a review. Plant Pathol 63(4):727–737

Perry RN, Moens M (2011) Introduction to plant-parasitic nematodes; modes of parasitism. In: Genomics and molecular genetics of plant-nematode interactions. Springer, Dordrecht, pp 3–20

Pettigrew WT, Meredith WR Jr, Young LD (2005) Potassium fertilization effects on cotton lint yield, yield components, and reniform nematode populations. Agron J 97(4):1245–1251

Prakash J, Singh K (2014) Impact of rice husk on population density and reproduction of tomato parasitised root-knot nematodes. Eur J Biotechnol Biosci 2(6):1–6

Rawal S (2020) A Review on Root-Knot Nematode Infestation and Its Management Practices through Different Approaches in Tomato. Trop Agroecosyst 1(2):92–96

Rehman B, Ganai MA, Parihar K, Asif M, Siddiqui MA (2015) Biopotency of oil cakes against Meloidogyne incognita affecting Vigna mungo. Asian J Crop Sci 7(2):128–137

Robinson AF (2002) Soil and plant interactions' impact on plant-parasitic nematode host finding and recognition. The behavioural ecology of parasites. CAB International, Wallingford, pp 89–110

Rompalli R, Mehendrakar SR, Venkata PK (2016) Evaluation of potential bio-control agents on root-knot nematode Meloidogyne incognita and wilt causing fungus Fusarium oxysporum f. sp. conglutinans in vitro. Afr J Biotechnol 15(19):798–805

Schouteden N, De Waele D, Panis B, Vos CM (2015) Arbuscular mycorrhizal fungi for the biocontrol of plant-parasitic nematodes: a review of the mechanisms involved. Front Microbiol 6:1280

Shakeel A, Khan AA, Haris M (2020) Multifaceted strategies used by root-knot nematodes to parasitize plants. Phyton 89(2):205–215

Shaltoot A (2001) Economic loss resulting from nematode-infected vegetables and fruits. In: Disease problems caused by nematodes in horticultural farms in Egypt Proceedings of a workshop (In Arabic), Menoufia Univ, pp 43–50

Sikandar A, Zhang MY, Zhu XF, Wang YY, Ahmed M, Iqbal MF, Javeed A, Xuan YH, Fan HY, Liu XY, Chen LJ, Duan YX (2019) Efficacy of Penicillium chrysogenum strain SNEF1216 against root-knot nematodes (Meloidogyne incognita) in cucumber (Cucumis sativus L.) under greenhouse conditions. Appl Ecol Environ Res 17(5):2451–12464. https://doi.org/10.15666/aeer/1705_1245112464

Sikora RA, Fernández E (2005) Nematodes parasites of vegetables. In: Liuc M, Sikora RA, Bridge J (eds) Plant parasitic nematodes in subtropical and tropical agriculture. CAB International, Wallingford, pp 319–392

Sikora RA, Pocasangre L, zum Felde A, Niere B, Vu TT, Dababat AA (2008) Mutualistic endophytic fungi and in-planta suppressiveness to plant parasitic nematodes. Biol Control 46(1):15–23

Silva JO, Santana MV, Freire LL, Ferreira BS, Rocha MR (2017) Bio control agents in the management of Meloidogyne incognita in tomato. Ciencia Rural 47:1–7. https://doi.org/10.1590/0103-8478cr20161053

Singh R, Kumar U (2015) Assessment of nematode distribution and yield losses in vegetable crops of Western Uttar Pradesh in India. Int J Sci Res 4(5):2812–2816

Singh T, Patel BA (2015) Management of root-knot nematode (Meloidogyne incognita) in bottle gourd using different botanicals in pots. J Parasit Dis 39(3):441–445

Smith SE, Smith FA (2011) Roles of arbuscular mycorrhizas in plant nutrition and growth: new paradigms from cellular to ecosystem scales. Annu Rev Plant Biol 62:227–250

Smith SE, Facelli E, Pope S, Smith FA (2010) Plant performance in stressful environments: interpreting new and established knowledge of the roles of arbuscular mycorrhizas. Plant Soil 326(1):3–20

Soliman MS, El-Deriny MM, Ibrahim DS, Zakaria H, Ahmed Y (2021) Suppression of root-knot nematode Meloidogyne incognita on tomato plants using the nematode trapping fungus Arthrobotrys oligospora Fresenius. J Appl Microbiol. https://doi.org/10.1111/jam.15101

Szabo M, Csepregi K, Galber M, Viranyi F, Fekete C (2012) Control plant-parasitic nematodes with Trichoderma species and nematode-trapping fungi: The role of chi18-5 and chi18-12 genes in nematode egg-parasitism. Biol Control 63(2):121–128

Szabo M, Urban P, Viranyi F, Kredics L, Fekete C (2013) Comparative gene expression profiles of Trichoderma harzianum proteases during in vitro nematode egg-parasitism. Biol Control 67(3):337–343

Teillet A, Dybal K, Kerry BR, Miller AJ, Curtis RH, Hedden P (2013) Transcriptional changes of the root-knot nematode Meloidogyne incognita in response to Arabidopsis thaliana root signals. Plos One 8(4):61259

Thoden TC, Korthals GW, Termorshuizen AJ (2011) Organic amendments and their influences on plant-parasitic and free-living nematodes: a promising method for nematode management. Nematology 13(2):133–153

Tikhonov VE, Lopez-Llorca LV, Salinas J, Jansson HB (2002) Purification and characterization of chitinases from the nematophagous fungi Verticillium chlamydosporium and V. suchlasporium. Fungal Genet Biol 35(1):67–78

Tosi S, Annovazzi L, Tosi I, Iadarola P, Caretta G (2002) Collagenase production in an Antarctic strain of Arthrobotrys tortor Jarowaja. Mycopathologia 153(3):157–162

Tunlid A, Johansson T, Nordbring-Hertz B (1991) Surface polymers of the nematode-trapping fungus Arthrobotrys oligospora. Microbiology 137(6):1231–1240

Verma AC, Anwar A (1996) Assessment of yield loss due to Meloidogyne incognita in pointed gourd (Trichosanthes dioica Roxb.). Afr Asian J Nematol 6:92–93

Viaene N, Coyne DL, Kerry BR (2006) Biological and cultural management. In: Perry RN, Moens M (eds) Plant nematology. CAB International, Wallingford, pp 346–369

Vierheilig H, Steinkellner S, Khaosaad T, Garcia-Garrido JM (2008). The biocontrol effect of mycorrhization on soilborne fungal pathogens and the autoregulation of the AM symbiosis: one mechanism, two effects?. In: Varma, A. (eds) Mycorrhiza. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-78826-3_15

Vigo C, Norman JR, Hooker JE (2000) Bio control of the pathogen Phytophthora parasitica by arbuscular mycorrhizal fungi is a consequence of effects on infection loci. Plant Pathol 49(4):509–514

Vos CM, Tesfahun AN, Panis B, De Waele D, Elsen A (2012) Arbuscular mycorrhizal fungi induce systemic resistance in tomato against the sedentary nematode Meloidogyne incognita and the migratory nematode Pratylenchus penetrans. Appl Soil Ecol 61:1–6

Vos CM, Yang Y, De Coninck B, Cammue BPA (2014) Fungal (-like) bio control organisms in tomato disease control. Biol Control 74:65–81

Wang CY, Wang Z, Fang ZM, Zhang DL, Gu LJ, Liu L, Sung CK (2010) Attraction of pinewood nematode to endoparasitic nematophagous fungus Esteya vermicola. Curr Microbiol 60(5):387–392

Wen Y, Meyer SL, MacDonald MH, Zheng L, Jing C, Chitwood DJ (2019) Nematotoxicity of Paeonia spp. extracts and Camellia oleifera tea seed cake and extracts to Heterodera glycines and Meloidogyne incognita. Plant Dis 103(9):2191–2198

Wesemael W, Viaene N, Moens M (2011) Root-knot nematodes (Meloidogyne spp.) in Europe. Nematology 13(1):3–16. https://doi.org/10.1163/138855410X526831

Widmer TL, Ludwig JW, Abawi GS (1999) The northern root-knot nematode on carrot, lettuce, and onion in New York. New York State Agricultural Experiment Station

Wieczorek K, Elashry A, Quentin M, Grundler FMW, Favery B, Seifert GJ, Bohlmann H (2014) A distinct role of pectate lyases in the formation of feeding structures induced by cyst and root-knot nematodes. Mol Plant Microbe Interactions 27(9):901–912

Xiang N, Lawrence KS, Donald PA (2018) Biological control potential of plant growth-promoting rhizobacteria suppression of Meloidogyne incognita on cotton and Heterodera glycines on soybean: A review. J Phytopathol 166:449–458. https://doi.org/10.1111/jph.12712

Xu LL, Lai YL, Wang L, Liu XZ (2011) Effects of abscisic acid and nitric oxide on trap formation and trapping of nematodes by the fungus Drechslerella stenobrocha AS6. 1. Fungal Biol 115(2):97–101

Yang H, Zhang Q, Dai Y, Liu Q, Tang J, Bian X (2014) Effects of arbuscular mycorrhizal fungi on plant growth depend on root system: a meta-analysis. Plant Soil 389:361–374. https://doi.org/10.1007/s11104-014-2370-8

Yang J, Liang L, Li J, Zhang KQ (2013) Nematicidal enzymes from microorganisms and their applications. App Microbiol Biot 97(16):7081–7095

Yang J, Liang L, Zhang Y, Li J, Zhang L, Ye F, Zhang KQ (2007a) Purification and cloning of a novel serine protease from the nematode-trapping fungus Dactylellina varietas and its potential roles in infection against nematodes. App Microbiol Biot 75(3):557–565

Yang J, Tian B, Liang L, Zhang KQ (2007b) Extracellular enzymes and the pathogenesis of nematophagous fungi. Appl Microbiol Biot 75:21–31

Yang J, Wang L, Ji X, Feng Y, Li X, Zou C, Zhang KQ (2011) Genomic and proteomic analyses of the fungus Arthrobotrys oligospora provide insights into nematode-trap formation. PLoS Pathog 7(9):e1002179

Yang Z, Yu Z, Lei L, Xia Z, Shao L, Zhang K, Li G (2012) Nematicidal effect of volatiles produced by Trichoderma spp. J Asia Pac Entomol 15(4):647–650

Yuhui B, Gao C, Yu Z (2018) Rhabdopeptides from Xenorhabdus budapestensis SN84 and their nematicidal activities against Meloidogyne incognita. J Agric Food Chem 66(15):3833–3839

Zamioudis C, Pieterse CM (2012) Modulation of host immunity by beneficial microbes. Mol Plant Microbe Interactions 25(2):139–150

Zhang K-Q, Hyde KD (2014) Nematode-trapping fungi. Springer, Dordrecht

Zhang S, Gan Y, Xu B (2015) Bio control potential of a native species of Trichoderma longibrachiatum against Meloidogyne incognita. Appl Soil Ecol 94:21–29

Zhou L, Yuen G, Wang Y, Wei L, Ji G (2016) Evaluation of bacterial biological control agents for control of root-knot nematode disease on tomato. Crop Prot 84:8–13

Amir Khan is Pursuing his Ph.D. at Plant Pathology and Nematology Section, Department of Botany, Aligarh Muslim University, Aligarh, India