

Review article

Sustainable management practices for plant-parasitic nematodes in pomegranate orchards in Egypt

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Abstract: Traditional plant-parasitic nematode (PPN) management in agriculture often relies on individual approaches, such as chemical nematicides or resistant cultivars. While these methods can offer persistent control, they often face limitations, including environmental concerns, nematode resistance development, and potential harm to non-target organisms. Therefore, this article aims to clarify the complexities and mechanisms of integrated pest management (IPM) as part of a paradigm shift toward integrated sustainable management (ISM). ISM acknowledges the complexities of nematode communities and their interactions with the soil ecosystem. It emphasizes the use of complementary strategies—such as biocontrol agents, cultural practices (including crop rotation and cover crops), and host plant resistance—in a synergistic manner. This holistic approach aims to naturally suppress PPN populations, minimize reliance on chemical interventions, and promote long-term soil health. Additionally, the article explores specific program proposals that exemplify this ISM approach, offering pomegranate growers practical solutions to achieve sustainable, profitable production while maintaining environmental well-being. By advocating for a shift towards ISM, this article aims to contribute to a more resilient and sustainable future for pomegranate cultivation and broader agricultural practices.

Keywords: PPNs control, Phytonematodes, Integrated pest management, Sustainable agriculture

Introduction

Pomegranate *Punica granatum* L. (Lythraceae) boasts a diverse array of cultivars, with estimates reaching approximately 500 globally (Stover and Mercure, 2007). In Egypt, seven cultivars dominate the landscape: Araby, Assuity, Hegazy, Manfalouty, Nab El Gamal, Wardi, and Wonderful (Ismail *et al.*, 2014; Amar and El-Zayat, 2017). The economic importance of

pomegranates is significant due to their increasing demand and consumption across regions such as India, Spain, Egypt, and the United States (Seth, 2003; Chandra *et al.*, 2010; Sepúlveda *et al.*, 2010). Pomegranate is important not only in agricultural production as a fruit tree but also as an ornamental plant, thanks to its showy flowers, which further enhance its economic value (Seth, 2003). Pomegranate cultivation has had a significant economic impact in these regions, with

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the fruit serving as a cultural icon in Egypt and India, driving high demand and economic importance (Taha, 2018; Kahramanoglu, 2019). Additionally, pomegranate is a prominent crude ingredient for various industries, including pharmaceuticals, cosmetics, beverages, and food, further enhancing its economic value (Bilgili and Genç, 2023; Valero-Mendoza *et al.*, 2023).

In Egypt, pomegranate cultivation has become a primary source of income for farmers, particularly in Upper Egypt, contributing to the economic sustainability of the agricultural sector. The cultivation of pomegranates has also expanded to newly reclaimed lands in Egypt, facilitated by the tree's drought tolerance, making it suitable for cultivation in dry weather and arid regions (CAPMAS, 2021). The economic importance of pomegranate is multifaceted, encompassing agriculture, industry, and trade. Egypt ranks seventh among the world's top pomegranate producers, with a cultivated area of 31,987 hectares and a production of 382,587 tonnes. In 2020, it further distinguished itself as the fifth largest exporter, shipping 82,866 tonnes (Ministry of Agriculture, 2020).

Plant-parasitic nematodes (PPNs) pose a significant threat to pomegranate production worldwide (Singh *et al.*, 2014; Sharma *et al.*, 2020; Mandal *et al.*, 2021), resulting in substantial economic losses due to reduced yield and fruit quality (Sharma *et al.*, 2020; Khan *et al.*, 2022). These microscopic pests damage the root system, hindering nutrient and water uptake, leading to stunted growth, smaller fruit size, and malformations (Khan *et al.*, 2022). Studies report yield reductions ranging from 20% to 70% due to PPNS, highlighting their critical impact on pomegranate profitability (Khan *et al.*, 2022). Therefore, effective control of PPNS is essential for ensuring sustainable and profitable pomegranate production (Singh *et al.*, 2014).

Therefore, the objectives of this review are to provide a comprehensive analysis of PPN management in pomegranate orchards by updating information on current strategies for managing PPNS, exploring strategies for sustaining the efficacy of these control methods, and proposing integrated pest management

(IPM) programs that optimize control efficiency while adhering to environmental sustainability standards.

1. Common species of PPNS infecting pomegranate

Pomegranate cultivation faces significant threats from diverse PPN species, which affect yield and fruit quality worldwide (Karssen and Moens, 2002; Sikora *et al.*, 2018; Yadav and Patil, 2021). Root-knot nematodes (RKNs), particularly *Meloidogyne incognita* and *M. javanica*, are widely reported to cause root galls, reduced growth, and yield losses (Singh *et al.*, 2019a; Hammad and El-Sagheer, 2022).

Other economically important PPNS include *Rotylenchulus reniformis*, which causes stunting, necrosis, and significant yield reduction (Darekar *et al.*, 1990), and *Pratylenchus* spp., which cause root damage and predispose plants to fungal diseases (Shelke and Darekar, 2001). Additionally, *Hoplolaimus indicus*, *Helicotylenchus* spp., and *Tylenchorhynchus* spp. contribute to the diverse PPN complex affecting pomegranates (El-Sherif and Abo-El-Ghar, 2012). Understanding the specific PPN species composition across different regions is crucial for implementing effective management strategies, such as deploying resistant cultivars, using soil solarization techniques, and employing biological control agents, to ensure sustainable and profitable pomegranate production (Karssen and Moens, 2002).

Some studies have revealed the widespread presence of PPNS in pomegranate orchards, with research highlighting diverse parasitic genera like root-knot nematodes (*Meloidogyne*), lesion nematodes (*Pratylenchus*), spear nematodes (*Paratrichodorus*), reniform nematodes (*Rotylenchulus*), sting nematodes (*Tylenchorhynchus*), dagger nematodes (*Longidorus*, *Xiphinema*), ring nematodes (*Criconemella*), spiral nematodes (*Helicotylenchus*), and stubby-root nematodes (*Tylenchorhynchus*) (Ibrahim *et al.*, 2010; El-Qurashi *et al.*, 2019; Singh *et al.*, 2019a; Poornima, 2020; Pradhan *et al.*, 2020; Katooli *et al.*, 2021; Hammad and El-Sagheer, 2022).

2. Damage and symptoms caused by nematodes on pomegranate

PPNs induce a range of aboveground and belowground symptoms in pomegranates (El-Sherif and Abo-El-Ghar, 2012; Sikora *et al.*, 2018). Root-knot nematodes are the most notorious culprits, inducing characteristic galls on roots. These galls disrupt water and nutrient uptake, resulting in stunted plant growth and reduced fruit size. The visible impacts of PPN infestation are equally varied, often resembling nutrient deficiencies or abiotic stress. Aboveground, pomegranate trees suffering from nematode infestations exhibit pathological symptoms, including:

- Chlorosis: yellowing of leaves due to impaired nutrient uptake.
- Wilting: drooping leaves and branches, reflecting water stress.
- Stunted growth: reduced plant height and internodal distance.
- Small and discolored fruits: compromised fruit development due to resource limitations.
- Premature leaf fall: early shedding of leaves further weakens the plant.

Beyond *Meloidogyne*, other nematode genera like *Pratylenchus* spp. and *Rotylenchulus reniformis* inflict damage by feeding on root tissues (Darekar *et al.*, 1990; Shelke and Darekar, 2001; El-Sagheer, 2019). This disrupts root functions, leading to symptoms similar to those caused by root-knot nematode infestations. Additionally, some nematodes, such as *Xiphinema* spp. and *Longidorus* spp., act as vectors for viruses, further compromising pomegranate health (Chitwood, 2002).

Belowground, pathological symptoms of PPNs often appear initially, causing a cascade of subtle yet detrimental symptoms that silently sabotage plant health. Root systems—the first line of defense against these microscopic invaders—bear the brunt of the attack. Galling and knotting, caused by root-knot nematodes of the *Meloidogyne* spp., disrupt water and nutrient uptake, leading to stunted growth and wilting (Agrios, 2005; El-Sagheer, 2019). Lesions and necrotic tissue, inflicted by lesion nematodes

(*Pratylenchus* spp.), stubby roots caused by stubby-root nematodes (*Trichodorus* spp.), and others, compromise root function and exacerbate susceptibility to pathogens (Poornima, 2020). Reduced root hair development, induced by species such as dagger nematodes (*Xiphinema* spp.), hinders nutrient acquisition and weakens overall plant resilience (Barker and Koenning, 1998). These belowground symptoms often ripple upwards, causing chlorosis, stunted foliage, and even premature fruit drop (Khosla and Sharma, 2024). While initially subtle, neglecting these tell-tale signs can lead to significant yield losses, highlighting the importance of proactive nematode management strategies.

3. Why controlling PPNs matters in pomegranate production

PPNs pose a significant threat to pomegranate production, causing substantial economic losses worldwide (Singh *et al.*, 2019a). These microscopic pests silently attack the root system, leading to a cascade of detrimental effects on plant health and yield. Controlling PPNs is crucial for several reasons:

3.1. Yield and quality losses

PPN infestation disrupts the root system, hindering water and nutrient uptake, resulting in stunted growth, reduced fruit size and quality, and ultimately, significant yield losses (Darekar *et al.*, 1990; El-Sherif and Abo-El-Ghar, 2012). Studies have reported yield reductions of up to 50% in pomegranate orchards heavily infested with PPNs (Darekar *et al.*, 1990).

3.2. Increased susceptibility to other diseases

Damaged roots caused by PPNs become susceptible to fungal and bacterial infections, further exacerbating the problem and leading to additional yield losses (Shelke and Darekar, 2001; Peng and Moens, 2003).

3.3. Long-term sustainability

Uncontrolled PPN populations can persist in the soil for long periods, posing a continuous threat

to future plantings and compromising the long-term sustainability of pomegranate orchards (Phani *et al.*, 2021).

3.4. Economic impact

PPN-induced yield losses result in significant economic losses for pomegranate growers, affecting their livelihoods and the industry's viability. Therefore, implementing effective control methods for PPNs is essential to ensure healthy, productive pomegranate orchards, safeguard yields, and maintain the economic sustainability of pomegranate production (Enyiukwu *et al.*, 2021).

4. Currently applied control strategies

Pomegranate cultivation faces a significant challenge from diverse PPNs, leading to substantial yield losses and economic damage (Sikora *et al.*, 2018). To protect pomegranate orchards, various control methods are currently employed, each offering distinct advantages and limitations:

4.1. Chemical nematicides

These remain a mainstay in PPN management, offering broad-spectrum control against various species, including the highly damaging *Meloidogyne incognita* and *M. javanica*

(Darekar *et al.*, 1990). However, concerns about environmental impact, potential resistance development, and high costs necessitate exploring alternative approaches.

Chemical nematicides have long been the cornerstone of PPN management in various agricultural settings, including pomegranate orchards (Darekar *et al.*, 1990; Askary and Abd-Elgawad, 2017; Singh *et al.*, 2019b). These synthetic compounds offer broad-spectrum control against diverse PPN species, including the highly damaging root-knot nematodes (RKNs) such as *M. incognita* and *M. javanica* (Darekar *et al.*, 1990). Despite their effectiveness in rapidly suppressing PPN populations and protecting crop yields, they have made them a popular choice for growers (Table 1). However, the continued reliance on chemical nematicides raises several concerns:

4.1.1. Environmental impact

Many chemical nematicides are persistent in the soil and can contaminate water resources, posing a threat to aquatic ecosystems and human health (Edwards and Cutler, 2000). Additionally, their application can disrupt beneficial soil organisms, which are vital for nutrient cycling and decomposition (Abd-Elgawad, 2021).

Table 1 Chemical group, common name, and mode of action for common nematicides.

Chemical group	Common name	Mode of action
Organophosphate	Cadusafos	Inhibits acetylcholinesterase, causing cholinergic poisoning
	Ethoprophos	
	Fenamiphos	
	Fosthiazate	
	Imicyafos	
Carbamate	Aldicarb	Inhibits acetylcholinesterase, causing cholinergic poisoning
	Carbofuran	
	Oxamyl	
Neonicotinoid	Imidacloprid	Agonizes nicotinic acetylcholine receptors, causing paralysis
Avermectin	Abamectin	Inhibits GABA receptors, causing paralysis
Pyridylethylamide	Fluopyram	inhibiting the enzyme succinate dehydrogenase (SDH, so-called complex II in the mitochondrial respiratory chain), disrupting energy production
Thiadiazin	Dazomet	Dazomet is used as a soil sterilant on a variety of sites such as golf courses, nurseries, turf sites, and potting soils. The decomposition of dazomet releases methyl isothiocyanate (MITC), a gas toxic to pests that would prevent or kill plant growth
Dithiocarbamate	Metam Sodium	Soil Fumigants
Dithiocarbamate	Metam Potassium	

4.1.2. Development of resistance

Overreliance on specific chemical nematicides can lead to the development of resistance in PPN populations, rendering them ineffective over time (Karssen and Moens, 2002). This necessitates the development of new nematicides and the constant rotation of different active ingredients to maintain control (Chen *et al.*, 2020).

4.1.3. High costs

Chemical nematicides are often expensive, posing a financial burden on growers, particularly small-scale farmers. This can limit access to effective PPN control measures and impact the sustainability of agricultural production (Jones, 2017; Ebone *et al.*, 2019).

4.1.4. Regulatory restrictions

Increasing environmental awareness and concerns about health risks have led to stricter regulations governing the use of certain chemical nematicides. This trend is likely to continue, further limiting the availability of these control options (Davis and Nendick, 2013).

Therefore, while chemical nematicides remain a valuable tool in PPN management, their use must be carefully considered in light of their environmental and economic implications. Exploring and implementing alternative control methods, such as biological control agents, resistant cultivars, and soil solarization, is crucial to developing sustainable, long-term solutions for managing PPNs in pomegranate orchards.

4.2. Soil solarization

This eco-friendly method harnesses the sun's heat to kill nematodes in the soil. Covering the soil with transparent plastic sheets for several weeks during the hottest months elevates soil temperature, effectively destroying PPNs while also suppressing soil-borne diseases (Shelke and Darekar, 2001). Soil solarization has emerged as a promising eco-friendly alternative to chemical nematicides for controlling PPNs in pomegranate orchards. This simple yet effective method utilizes solar energy to heat the soil,

killing nematodes and other harmful soil-borne pathogens (Marahatta *et al.*, 2012). The process involves:

- (a). Moistening the soil: Deeply watering the soil to a depth of 40-60 cm ensures efficient heat transfer and maximizes nematode mortality.
- (b). Covering the soil: Transparent plastic sheets with a thickness of 0.02-0.03 mm are used to cover the moist soil, trapping the solar heat within the soil profile.
- (c). Maintaining the seal: The edges of the plastic sheets are buried firmly in the soil to prevent heat loss and ensure optimal solarization conditions.
- (d). Duration: The solarization period typically lasts for 4-6 weeks during the hottest months of the year, when solar radiation is most intense.

This heat treatment effectively suppresses various PPNs, including *M. incognita*, *M. javanica*, and *R. reniformis*, which are major threats to pomegranate production. Studies have reported significant reductions in nematode populations of up to 90% following soil solarization (Shelke and Darekar, 2001). Soil solarization offers several advantages over chemical nematicides:

- (a). Environmentally friendly: It avoids the use of harmful chemicals, protecting the environment and human health.
- (b). Broad-spectrum control: It effectively controls a wide range of PPNs, reducing the risk of resistance development.
- (c). Cost-effective: It requires minimal investment compared to expensive chemical nematicides, making it accessible to small-scale farmers.
- (d). Sustainable: It improves soil health by suppressing soil-borne diseases and promoting beneficial soil microbes.

However, soil solarization also has limitations:

- (a). weather dependent: Its effectiveness depends on sufficient sunlight and warm temperatures, limiting its applicability in cooler regions or during cloudy periods.
- (b). Time-consuming: The required solarization period can delay planting and reduce cropping intensity.

(c). Large-scale implementation: Covering large areas can be challenging and labor-intensive.

Despite these limitations, soil solarization remains a valuable tool for integrated pest management (IPM) programs in pomegranate orchards. Its eco-friendly nature and effectiveness against various PPNs make it a sustainable and promising approach for protecting pomegranate yields and promoting long-term orchard health.

4.3. Biofumigation

This environmentally friendly strategy involves incorporating specific plant materials, such as marigold and mustard, into the soil (Chitwood, 2002; Reddy, 2011; Das and Behera, 2019; Brennan *et al.*, 2020). These plants release volatile compounds toxic to nematodes, providing a sustainable control option (Das and Behera, 2019). Biofumigation offers a promising, environmentally friendly alternative for managing PPNs in pomegranate orchards (Reddy, 2011; Eisenback, 2018). This method involves incorporating specific plant materials into the soil, releasing volatile compounds that are toxic to nematodes. Among the most effective biofumigant plants are: (a). Brassicaceae family: Plants like mustard, rapeseed, and marigold release isothiocyanates, potent fumigants that disrupt nematode development and reproduction (Fourie *et al.*, 2016).

(b). Cruciferous plants: Broccoli, cauliflower, and cabbage are effective biofumigants, releasing various nematicidal compounds including glucosinolates and their breakdown products (Chitwood, 2002; Al-Abed *et al.*, 2022).

(c). Sorghum spp.: Great millet, *Sorghum bicolor*, releases hydrogen cyanide, a volatile gas that effectively kills nematodes in the soil (Paudel *et al.*, 2025).

The effectiveness of biofumigation depends on several factors, including:

(a). Type and amount of plant material: The specific plant species and its biomass determine the quantity and type of nematicidal compounds released.

(b). Soil conditions: Moisture content, temperature, and soil texture influence the release, diffusion, and activity of biofumigant compounds.

(c). Nematode species: Different PPN species vary in their susceptibility to biofumigants.

(d). Studies have shown that biofumigation can significantly reduce PPN populations in pomegranate orchards, leading to improved plant growth and yield (El-Sherif and Abo-El-Ghar, 2012).

Its advantages include:

(a). Eco-friendly: It avoids harmful chemicals, protecting the environment and promoting soil health.

(b). Sustainable: It increases organic matter content and improves soil structure, leading to long-term benefits.

(c). Cost-effective: Utilizing readily available plant materials makes it an affordable option for farmers.

(d). Broad-spectrum control: It can suppress various PPN species, reducing the risk of resistance development.

However, biofumigation also has limitations:

(a). Time-consuming: Decomposing plant material takes time, delaying planting and potentially reducing cropping intensity.

(b). Variable effectiveness: The effectiveness can be influenced by various factors, requiring careful consideration of soil conditions and nematode species.

(c). Large-scale implementation: Incorporating large quantities of biomass can be labor-intensive and challenging.

Despite these limitations, biofumigation remains a valuable tool for managing PPNs in pomegranate orchards. Its eco-friendly nature, cost-effectiveness, and broad-spectrum control make it a promising component of IPM programs, promoting sustainable pomegranate production and protecting both the environment and human health.

4.4. Biological control agents

Biological control offers a promising strategy for managing PPNs in pomegranate orchards, promoting biodiversity and reducing reliance on

harmful chemicals (Karssen and Moens, 2002; Ahmad *et al.*, 2021). This approach leverages natural enemies of PPNs, including:

(a). Predatory nematodes

These microscopic pests actively hunt and feed on PPNs, effectively reducing their populations (Bilgrami, 2008). Predatory nematodes, particularly species belonging to the orders Mononchida, Diplogasterida, Dorylaimida, and Aphelenchida (Bilgrami *et al.*, 2005), which are known as diplogasterid predators (characterized by a cutting and sucking feeding apparatus type), may be more prevalent due to their widespread application. However, other families are categorized as dorylaimid predators based on the design type of their feeding apparatus (piercing and sucking), such as Monohysterida, Bathyodontina, and Actinolaimoidea (Esser, 1987). All these groups offer a valuable and sustainable approach to controlling PPNs (Bilgrami, 2008). They consume both plant-parasitic nematodes and soil microbes. They serve two purposes: first, they reduce the number of plant-parasitic nematodes across all soil types; second, they release nutrients in forms that plants can utilize, allowing them to tolerate nematode load on their roots more effectively (Bilgrami, 2008; Kanwar *et al.*, 2021). Notably, species such as *Mononchus aquaticus*, *Mononchus papillatus*, and *Pristionchus pacificus* have demonstrated significant potential for controlling economically important PPNs, including *Meloidogyne* spp. and *Heterodera* spp. (Khan and Kim, 2007; Bilgrami *et al.*, 2008). Moreover, research suggests that predatory nematodes can be cultured effectively in controlled environments, making them a readily available, commercially viable option for PPN biocontrol (Bilgrami and Brey, 2005; Nguyen and Grewal, 2006).

(b). Entomopathogenic nematodes

Entomopathogenic nematodes (EPNs) offer a promising approach for sustainable agriculture as biocontrol agents against plant-parasitic nematodes (PPNs). These nematodes, primarily from the genera *Steinernema* and

Heterorhabditis, naturally parasitize insect hosts and harbor symbiotic bacteria, including *Xenorhabdus* spp. in *Steinernema* and *Photorhabdus* spp. in *Heterorhabditis*, which contribute to host mortality. While their primary role is insect control, studies suggest that certain EPNs may indirectly suppress PPN populations by altering soil microbial communities or competing for resources (Kaya and Gaugler, 1993; Grewal *et al.*, 2005; Koppenhöfer, 2007). This efficient predatory behavior, coupled with their environmental safety and compatibility with other IPM practices, makes EPNs a compelling alternative to chemical nematicides (Kaya and Gaugler, 1993). Studies have demonstrated their efficacy against diverse PPN species, including root-knot nematodes and citrus nematodes, with significant improvements in crop yield documented (Koppenhöfer, 2007). Further research on optimizing application strategies, identifying effective EPN-bacteria combinations for specific PPN targets, and addressing potential soil factors that limit their efficacy is crucial to unlocking the full potential of these natural warriors in protecting our crops from harmful nematodes.

(c). Fungi

Fungi offer a promising alternative to chemical control of plant-parasitic nematodes, with several species exhibiting effective biocontrol potential (Table 2). Whether directly or indirectly, they affect the plant's tolerance to infection (Akhtar *et al.*, 2015). Notably, *Paecilomyces lilacinus* (now known as *Purpureocillium lilacinum*) and *Trichoderma* spp. are widely recognized for their ability to trap and penetrate nematodes with adhesive networks of hyphae (Sivakumar and Gomathinayagam, 2018; Lombardi, 2020). Similarly, *Verticillium lecanii* and *Hirsutella rhossiliensis* employ adhesive hyphae and conidia, respectively, to capture and kill nematodes. Additionally, specialized parasitic fungi, such as *Nematophthora gynophila*, directly infect and eliminate nematodes, offering another valuable biocontrol strategy (Sivakumar and Gomathinayagam, 2018). These fungi, along with *Arthrobotrys oligospora* and *Drechslera*

coniospora, utilizing adhesive traps and conidia for nematode capture, highlight the diverse array of fungal mechanisms employed in plant-parasitic nematode biocontrol (Siddiqui and Mahmood, 1996; Jiang *et al.*, 2017; Singh *et al.*, 2019a).

(d). Bacteria

Bacteria represent another sustainable alternative to chemical control in managing plant-parasitic nematodes, offering multiple mechanisms to suppress nematode populations and enhance plant resilience (Table 3). Among the most studied genera, *Pasteuria penetrans* is a well-known obligate parasite that infects nematodes by adhering its spores to their cuticle, eventually impairing their reproduction and mobility (Davies *et al.*, 2011). Similarly, *Pseudomonas fluorescens* produces metabolites

such as hydrogen cyanide and phenazines, which exhibit nematicidal activity and induce systemic resistance in plants (Siddiqui and Shaukat, 2003). Additionally, *Bacillus subtilis* and *Bacillus firmus* have been reported to suppress nematode activity through the secretion of lipopeptides and proteases, which degrade the nematode cuticle and inhibit egg hatching (Xiang *et al.*, 2017). Some bacterial species, such as *Serratia marcescens*, produce chitinases that break down nematode eggshells, thereby reducing their ability to complete their life cycle (Mhatre *et al.*, 2019). Overall, bacteria offer a diverse and eco-friendly approach to biological control, providing direct antagonism and promoting plant growth to mitigate nematode damage (El-Hadad *et al.*, 2011).

Table 2 Most important fungi used as biocontrol agents for PPNs.

Fungus	Family	Common name	Mode of action	Reference
<i>Paecilomyces lilacinus</i> (now <i>Purpureocillium lilacinum</i>)	Ophiocordycipitaceae	Lilac fungus	Parasitism by trapping and penetrating nematodes with adhesive networks of hyphae	Tandingan, and Asuncion, (1990)
<i>Verticillium lecanii</i>	Plectosphaerellaceae	Lecanium Verticillium	Nematophagous fungi that trap and penetrate nematodes with adhesive hyphae	Meyer, and Meyer, (1996)
<i>Hirsutella rhossiliensis</i>	Ophiocordycipitaceae	Hairy fungus	Nematophagous fungi that produce adhesive conidia that attach to and penetrate nematodes	Lackey <i>et al.</i> , (1993)
<i>Nematophthora gynophila</i>	Neocallimastigomycota	Nematode-killing fungus	Specialized parasitic fungus that infects and kills nematodes	Crump and Moore, (1990)
<i>Arthrobotrys oligospora</i>	Orbiliaceae	Sticky trap fungus	Nematophagous fungi that produce adhesive traps that capture and constrict nematodes	Tunlid, and Jansson, (1991)
<i>Drechmeria coniospora</i>	Moniliaceae	Nematode-killing fungus	Nematophagous fungi that produce adhesive conidia that attach to and penetrate nematodes	Dijksterhuis <i>et al.</i> , (1990)
<i>Trichoderma harzianum</i>	Hypocreaceae	Green mold	Induces plant resistance to nematodes by triggering defense responses	Mendes <i>et al.</i> (1996)
<i>Glomeromycota</i> (Mycorrhizal fungi)	Glomeromycota	Mycorrhizae	Enhance plant growth and vigor, improving tolerance to nematode damage	Siddiqui <i>et al.</i> , (1998)
<i>Fusarium oxysporum</i>	Nectriaceae	Fusarium wilt	Nematophagous fungus with trapping and toxin-producing abilities	Barron (1977)
<i>Monacrosporium ellipsosporum</i>	Monacrosporiaceae	Sticky spore fungus	Nematophagous fungus with adhesive hyphae and conidia	Barron (1977)
<i>Gliocladium roseum</i>	Hypocreaceae	Pink mold	Produces toxins (gliocladins) that inhibit nematode growth and development	Mendes <i>et al.</i> (2020)
<i>Pochonia chlamydosporia</i>	Clavicipitaceae	Chlamydospore fungus	Produces enzymes that degrade the cuticle of nematodes	Mendes <i>et al.</i> (2020)
<i>Beauveria bassiana</i>	Cordycipitaceae	White mold	Produces toxins (beauvericin) and enzymes that kill nematodes	Mendes <i>et al.</i> (2020)
<i>Metarhizium robertsii</i>	Cordycipitaceae	Green mold	Produces toxins (metarhizins) and enzymes that kill nematodes	Mendes <i>et al.</i> (2020)
<i>Trichoderma longibrachiatum</i>	Hypocreaceae	Long-branched Trichoderma	Induces systemic resistance in plants, reducing nematode damage	Singh <i>et al.</i> (2018)
<i>Clonostachys rosea</i>	Nectriaceae	Pink fungus	Produces toxins (pyrones) that inhibit nematode hatching and development	Singh <i>et al.</i> (2018)
<i>Chaetomium globosum</i>	Chaetomiaceae	Black mold	Produces toxins (chaetoglobosins) that inhibit nematode growth and reproduction	Singh <i>et al.</i> (2018)
<i>Penicillium simplicissimum</i>	Trichocomaceae	Penicillium mold	Produces toxins (penicillins) that disrupt nematode cell walls	Singh <i>et al.</i> (2018)
<i>Aspergillus niger</i>	Aspergillaceae	Black mold	Produces enzymes (chitinases) that degrade the nematode cuticle	Singh <i>et al.</i> (2018)
<i>Piriformospora indica</i>	Sebacinaceae	Piriformospora	Induces systemic resistance in plants, improving tolerance to nematodes	Singh <i>et al.</i> (2018)

Table 3 Most important bacteria used in the biological control of PPNs.

Bacteria	Family	Mode of action	Reference
<i>Pasteuria penetrans</i>	Pasteuriaceae	Endoparasitic; spores adhere to nematode cuticle, penetrate, and inhibit reproduction	Davies <i>et al.</i> , 2011
<i>Pseudomonas fluorescens</i>	Pseudomonadaceae	Produces hydrogen cyanide and phenazines, exhibiting nematocidal activity and inducing systemic resistance in plants	Siddiqui and Shaukat, 2003
<i>Bacillus subtilis</i>	Bacillaceae	Produces lipopeptides and proteases that degrade nematode cuticle and inhibit egg hatching	Xiang <i>et al.</i> , 2017
<i>Bacillus firmus</i>	Bacillaceae	Secretes enzymes that degrade nematode eggshells, affecting juvenile development	Xiang <i>et al.</i> , 2017
<i>Serratia marcescens</i>	Enterobacteriaceae	Produces chitinases that degrade nematode eggshells, disrupting reproduction	Mhatre <i>et al.</i> , 2019
<i>Bacillus spp.</i> (various)	Bacillaceae	Induces plant defense responses, produces toxic metabolites, and disrupts nematode development	El-Hadad <i>et al.</i> , 2011

(e). Algae

A particular marine species has emerged as a promising biocontrol agent against PPNs. It indirectly affects the nematode environment, whether in the soil or within plant tissues (Paracer *et al.*, 1987; Fan *et al.*, 2023). Studies have demonstrated that various algal extracts and compounds possess nematocidal properties, effectively reducing PPN populations and mitigating crop damage (Abdel-Motaal *et al.*, 2019; El-Nagdi *et al.*, 2023). The effectiveness of these extracts is attributed to the presence of bioactive molecules, including phlorotannins, polysaccharides, and fatty acids (Abdel-Motaal *et al.*, 2019; El-Nagdi *et al.*, 2023). Phlorotannins, for example, have been shown to disrupt nematode egg development and hatching, while polysaccharides can act as physical barriers, hindering nematode mobility and penetration into plant roots (Veronico and Melillo, 2021). Moreover, certain algae, such as *Ulva fasciata* and *Ecklonia maxima*, have demonstrated nematocidal activity against root-knot nematodes, highlighting their potential in protecting crops from these harmful pests (El-Nagdi *et al.*, 2023).

Generally, while chemical nematicides offer quick control, their use poses environmental concerns and risks to soil health. In contrast, biological control agents, though promising, present unique challenges. These natural enemies boast several advantages: they are environmentally friendly, establish long-term suppression, target PPNs specifically, and minimize the development of resistance. However, their implementation presents hurdles. Efficient mass production can be costly;

delivering them to reach PPN populations demands appropriate methods, and environmental factors can impact their effectiveness. Balancing the benefits of biological control with overcoming these challenges is crucial for sustainable management of plant-parasitic nematodes.

Despite these challenges, biological control is a promising and rapidly evolving approach for managing PPNs in pomegranate orchards. Research and development efforts are focused on improving the development of algae-based compounds and optimizing application methods. By integrating biological control with other IPM practices, pomegranate growers can achieve sustainable, environmentally friendly management of PPNs, ensuring healthy, productive orchards.

4.5. Resistant rootstock cultivars

Developing and deploying plant cultivars with resistance to specific PPNs is a crucial long-term strategy (Peng and Moens, 2003; Long *et al.*, 2012). These resistant rootstocks hinder nematode development and reduce damage, significantly contributing to orchard health (Ferris *et al.*, 2012). Resistant rootstocks harbor specific genetic traits that hinder nematode development, reproduction, and feeding, significantly reducing damage to the pomegranate scion (Loreti, 2008; Singh *et al.*, 2019a). This approach provides several advantages over other control methods:

(a). Long-term protection: Once established, resistant rootstocks provide lasting protection against PPNs, thereby minimizing the need for repeated applications of nematicides or other

control measures (Van der Putten *et al.*, 2006; Korthals *et al.*, 2014).

(b). Reduced reliance on chemicals: This approach reduces dependence on environmentally harmful chemical nematicides, promoting soil health and protecting human health (Molinari, 2011).

(c). Increased productivity: Resistant rootstocks ensure healthy root systems, leading to improved plant vigor, higher yields, and better fruit quality (Eisenhauer *et al.*, 2010).

(d). Sustainable management: By reducing the need for chemical interventions, resistant rootstocks promote sustainable pomegranate production practices (Puissant *et al.*, 2021).

Several pomegranate rootstock cultivars exhibiting resistance to specific PPNs have been developed through breeding programs (Cabrera and El-Borai, 2018). For example, cultivars like 'Alandi' and 'Ganja' offer resistance to *Meloidogyne incognita* and *M. javanica*, while 'Hicaznar' is resistant to *Rotylenchulus reniformis* (El-Sherif and Abo-El-Ghar, 2012). However, developing new resistant rootstocks is a lengthy and complex process that requires extensive research, breeding efforts, and field testing. Additionally, resistance can break down over time due to evolving nematode populations, necessitating the continuous development of new resistant cultivars. Despite these challenges, resistant rootstocks remain a crucial component of IPM programs for controlling PPNs in pomegranate orchards. By utilizing available resistant cultivars and actively developing new ones, growers can achieve sustainable, environmentally friendly nematode control, ensuring healthy, productive pomegranate orchards for future generations.

4.6. Integrated PPN management

Combining various control methods synergistically maximizes their effectiveness while minimizing potential drawbacks. IPM programs tailored to specific PPN species and orchard conditions offer the most sustainable and long-term solution for managing PPNs in pomegranate production. Successfully managing PPNs in pomegranate orchards requires a

strategic and multifaceted approach (Phani *et al.*, 2021; Karuri, 2022). Integrated pest management (IPM) provides a framework for combining various control methods, maximizing their effectiveness while minimizing environmental impact and promoting long-term sustainability (Dutta *et al.*, 2019; Sikora *et al.*, 2018).

IPM programs for PPN management in pomegranate often include:

(a). Resistant Rootstock Cultivars: Utilizing rootstocks resistant to specific PPN species offers long-term protection and reduces reliance on chemical interventions (Williamson and Kumar, 2006; Singh *et al.*, 2019a). These resistant cultivars often express or accumulate defense-related biochemical compounds such as phenolic acids, lignin, tannins, and flavonoids, which hinder nematode penetration, development, or reproduction (Williamson and Kumar, 2006). Moreover, enzymes such as peroxidase (POD), polyphenol oxidase (PPO), and phenylalanine ammonia-lyase (PAL) are frequently upregulated in resistant rootstocks, thereby reinforcing structural barriers and activating systemic defense responses (Molinari, 2011). This combination of genetic resistance and induced biochemical defenses makes resistant rootstocks a highly effective and sustainable strategy for PPN management (Singh *et al.*, 2019a).

(b). Soil Amendments: Incorporating organic matter, such as compost and cover crops, improves soil health and can suppress nematode populations (El-Sherif and Abo-El-Ghar, 2012).

(c). Biofumigation: Planting specific crops, such as marigolds and mustard, releases volatile compounds that kill or repel nematodes, offering an eco-friendly control method (Chitwood, 2002).

(d). Biological Control: Introducing bacteria and fungi provides natural enemies to control PPN populations (Karssen and Moens, 2002).

(e). Cultural Practices: Implementing practices like crop rotation, sanitation, and irrigation management can disrupt PPN life cycles and reduce their spread (Akhtar and Siddiqui, 2008).

(f). Monitoring and Decision Making: Regularly monitoring PPN populations and utilizing

diagnostic tools enables targeted interventions and prevents the unnecessary application of control measures (Pun *et al.*, 2023).

Generally, compared to single-method approaches, IPM programs offer a multifaceted approach to tackling PPNs, boasting several key advantages. Firstly, by combining diverse control methods—such as biocontrol agents, cultural practices, and targeted nematicide applications—IPM enhances overall effectiveness, resulting in superior suppression of PPNs. Secondly, it minimizes reliance on chemical nematicides, protecting the environment, promoting soil health, and mitigating concerns about harmful residues. Thirdly, its focus on long-term management strategies fosters sustainable nematode control and reduces the risk of resistance development—a major threat associated with single-method approaches. Ultimately, by optimizing control strategies to address specific needs and minimize unnecessary interventions, IPM enhances economic viability for growers, thereby increasing both crop yields and profitability. In essence, IPM offers a holistic and sustainable approach to managing PPNs, ensuring healthy crops and a thriving agricultural ecosystem. By adopting an IPM approach, pomegranate growers can effectively manage PPNs while safeguarding the environment and ensuring sustainable production for future generations.

6. Proposed sustainable programs

PPNs pose a significant threat to pomegranate production, causing substantial yield losses and economic damage. To effectively manage these microscopic pests and protect orchard health, a comprehensive and integrated approach is crucial. Here, we suggest a program incorporating various control methods for sustainable PPN management in pomegranate orchards:

(a). Resistant rootstock cultivars (Foundation)

The program's cornerstone should be the utilization of pomegranate rootstocks resistant to specific PPN species prevalent in the region. Cultivars like 'Alandi', 'Ganja', and 'Hicaznar'

offer resistance to various nematode species, providing long-term protection and reducing reliance on other control methods (Singh *et al.*, 2019a).

(b). Soil health enhancement

Promoting soil health is crucial in suppressing nematode populations. Practices such as incorporating organic matter (compost, cover crops) and implementing proper irrigation management improve soil structure, increase beneficial microbial activity, and create an environment less favorable to nematodes (El-Sherif and Abo-El-Ghar, 2012).

(c). Biofumigation and biological control

These eco-friendly methods utilize natural processes to control PPNs. Planting biofumigant crops, such as marigolds and mustard, releases volatile compounds toxic to nematodes. Introducing predatory nematodes and fungi provides natural enemies that directly suppress nematode populations (Chitwood, 2002; Karssen and Moens, 2002).

(d). Cultural practices

While chemical nematicides remain a mainstay in control, concerns regarding environmental impact and the development of resistance have prompted exploration of sustainable alternatives (Mitreva *et al.*, 2007). Among these, cultural practices offer a versatile and eco-friendly approach to managing nematode populations and safeguarding crop production (Omran *et al.*, 2023).

- **Soil amendments:** Soil amendment offers another avenue for cultural control. Organic materials, such as compost or green manure, can stimulate the activity of beneficial microorganisms, including fungal antagonists and predatory nematodes, which suppress nematode populations through competition and parasitism (Karssen and Moens, 2002). Biofumigation techniques, utilizing the release of volatile compounds from certain plants (e.g., Brassicaceae species) upon soil incorporation, can also effectively reduce nematode numbers and improve soil health (Dutta *et al.*, 2019).

While individual cultural practices may not provide the same level of control as chemical nematicides, their cumulative impact can be substantial (Timper, 2014). Moreover, these practices offer additional benefits, including improved soil fertility, increased organic matter content, and enhanced water-holding capacity (Silva *et al.*, 2018).

- **Removing infected plant debris:**

Several studies highlight the efficacy of this technique. In their work on citrus orchards, Duncan *et al.* (2020) observed a 50% reduction in nematode numbers following the removal and burning of infected tree roots. Similarly, a study by Sikora *et al.* (2005) on vegetable crops showed that eliminating weed and crop residues infested with root-knot nematodes (*Meloidogyne* spp.) led to a 75% decline in nematode populations compared to untreated controls. The logic behind this effectiveness is straightforward. Nematodes rely on infested plant material for food and reproduction. Removing this source cuts off their life cycle, preventing further build-up and limiting their spread to new plants. Additionally, eliminating debris reduces the likelihood that vectors, such as wind and water, will disperse PPNs to uninfested areas. Removing infected plant debris is most effective when combined with other control methods. For instance, integrating it with soil solarization, where the soil is covered with plastic to trap solar heat and kill PPNs, can significantly enhance the effectiveness of both practices. Similarly, combining debris removal with crop rotation, in which different plant families are grown in sequence, disrupts the nematode life cycle and further depletes nematode populations.

(e). Monitoring and decision making

Effective PPN control hinges on proactive and informed decision-making, fueled by meticulous monitoring. Unthinkingly applying broad-spectrum nematicides or implementing generic control strategies is no longer a sustainable approach. Instead, a data-driven approach, based on accurate nematode identification and population quantification, empowers growers to

implement targeted, cost-effective interventions. The cornerstone of PPN monitoring lies in soil sampling and analysis. Techniques such as nematode extraction and identification enable growers to identify specific nematode species, assess population density, and track their distribution within the field. This information is crucial for choosing the most effective control method, as different nematode species have varying susceptibilities to specific chemicals, biological agents, and cultural practices (Duncan *et al.*, 2016). Monitoring goes beyond mere population assessments. Tracking nematode activity throughout the growing season, particularly during critical stages like seedling emergence and root development, provides valuable insights into their impact on crop health. Tools such as serological assays and molecular diagnostics can detect nematode presence even before symptoms appear, enabling early intervention and preventing significant yield losses (Sipes *et al.*, 2010). The gathered data forms the basis for informed decision-making. Economic thresholds, which estimate the PPN population density at which control measures become economically justified, serve as valuable aids in decision-making. By comparing nematode population levels to these thresholds, growers can avoid unnecessary or premature interventions, saving resources and minimizing environmental impact (Westphal, 2011). Furthermore, integrating monitoring data with environmental factors, such as soil temperature and moisture, along with crop rotation plans and previous control practices, builds a comprehensive picture of nematode dynamics within the field. This enables growers to implement IPM strategies that combine multiple control methods, such as resistant cultivars, cover crops, and biofumigation, for sustainable, long-term nematode suppression (Grewal *et al.*, 2020).

(f). Chemical nematicides

Chemical nematicides should be used as a last resort, primarily for managing severe infestations or PPN species that are not controlled by other methods. Careful selection of

environmentally friendly nematicides and adherence to proper application practices are crucial to minimize potential environmental and health risks.

(g). Continuous research and development

Ongoing research and development efforts play a crucial role in enhancing existing control methods and developing innovative approaches for managing PPNs. This includes investigating new biocontrol agents, breeding more resistant rootstock cultivars, and exploring alternative nematicidal compounds.

By implementing this multi-pronged approach, pomegranate growers can effectively manage PPNs, ensure the sustainability of their orchards, and protect the environment for future generations. Remember, the specific combination of control methods will depend on the specific PPN species present, orchard conditions, and economic considerations.

7. Integrated sustainable management (ISM)

Managing PPNs in pomegranate orchards requires a sustainable approach that balances effective control with environmental responsibility (Taylor and Georgis, 1979; Montanaro *et al.*, 2017; Sivasubramaniam *et al.*, 2020). Conventional reliance on chemical nematicides, while offering rapid control, presents a double-edged sword. Long-term use compromises soil health by disrupting microbial communities and increasing leaching, which can pollute water resources (Aballay *et al.*, 2020). Furthermore, PPNs readily develop resistance to these chemicals, rendering them ineffective and necessitating ever-increasing application rates, further exacerbating environmental concerns (Taylor and Georgis, 1979). Therefore, adopting sustainable management practices is paramount for ensuring long-term orchard health, environmental protection, and ultimately, food security (Montanaro *et al.*, 2017).

8. The future of control

Combating PPNs in pomegranate orchards requires continuous innovation and exploration of novel approaches (Hammad and El-Sagheer,

2022). While current control methods offer valuable tools, the future of nematode management lies in the development of sustainable and environmentally friendly technologies. Here, we explore some promising avenues shaping the future of PPN control in pomegranate:

(a). **Precision agriculture:** Utilizing advanced technologies, such as drones, sensors, and data analytics, can enable precise management of PPNs. By mapping nematode populations within the orchard, growers can target control measures to specific areas, minimizing unnecessary interventions and optimizing resource allocation (Pun *et al.*, 2023).

(b). **RNA interference (RNAi):** This innovative technology disrupts gene expression in nematodes, hindering their development and reproduction. Research on RNAi-based nematicides has shown promising results, offering a targeted, environmentally friendly control option for the future (Lilley *et al.*, 2012).

(c). **Genome editing:** CRISPR-Cas9 and other genome editing tools hold immense potential for developing pomegranate varieties resistant to PPNs. By editing specific genes responsible for susceptibility, scientists can create cultivars with inherent resistance to specific nematode species (Barker and Koenning, 1998; Zamanian and Andersen, 2016).

(d). **Nanotechnologies:** Nanoparticles offer a unique platform for delivering nematicidal agents directly to nematodes (Bhau *et al.*, 2016; Hammad and El-Sagheer, 2022). These targeted delivery systems can significantly enhance the effectiveness of control measures while minimizing environmental impact (Bhau *et al.*, 2016).

(e). **Enhanced biocontrol agents:** Research focuses on improving the efficacy and application methods of biocontrol agents, such as predatory nematodes and fungi (Abd-Elgawad, 2020; Molinari and Leonetti, 2019). By developing more potent strains and optimizing their

application strategies, biocontrol can become a cornerstone of sustainable PPN management (Abd-Elgawad, 2020).

(f). **Novel nematicides:** Scientists are exploring diverse avenues for developing new nematicides with improved environmental profiles and reduced risk of resistance development. These include natural compounds derived from plants and microbes, as well as synthetic molecules targeting specific nematode pathways (Giannakou *et al.*, 2004).

The future of PPN control in pomegranate orchards lies in a combination of these emerging technologies and strategies (Tefu, 2020). By integrating these advancements with established methods, such as resistant rootstocks and cultural practices, growers can achieve effective and sustainable control, safeguarding their orchards and the environment for generations to come.

9. Conclusion

Plant-parasitic nematodes (PPNs) pose a significant challenge to pomegranate production, resulting in substantial yield losses and economic setbacks. Effective management of these microscopic pests requires a scientifically sound, integrated approach that ensures both immediate control and long-term sustainability.

A holistic management strategy should incorporate resistant rootstocks, biological control agents, soil health enhancement, cultural practices, and targeted interventions. The use of nematode-resistant pomegranate rootstocks, such as 'Alandi', 'Ganja', and 'Hicaznar', provides a foundational defense against PPN species, reducing dependency on chemical nematicides. Additionally, promoting soil biodiversity through organic amendments, biofumigation, and beneficial microbial inoculations enhances the natural suppression of nematodes.

Biological control measures, such as the nematophagous fungi *Trichoderma* spp. and the bacterial antagonist *Pasteuria penetrans*, should be prioritized to minimize chemical inputs. Cultural practices such as cover cropping, sanitation, and optimized irrigation play a crucial role in disrupting nematode life cycles and

reducing population density. Continuous research and adoption of innovative technologies, such as RNA interference (RNAi)-based nematode control, environmentally friendly biopesticides, and precision agriculture tools for early detection of nematodes, are essential for enhancing control efficiency. Regular monitoring and nematode population assessments will ensure timely interventions, preventing outbreaks and unnecessary chemical applications.

By integrating these diverse yet complementary management strategies, pomegranate growers can achieve sustainable PPN control, safeguard soil health, and enhance orchard resilience. This multi-pronged approach not only ensures the economic viability of pomegranate production but also contributes to environmental conservation and long-term agricultural sustainability.

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شیوه‌های مدیریت پایدار برای نماتدهای انگل گیاهی در باغ‌های انار مصر

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چکیده: مدیریت سنتی نماتدهای انگل گیاهی (PPN) در کشاورزی اغلب به رویکردهای فردی، مانند نماتدکشی‌های شیمیایی یا ارقام مقاوم، متکی است. با وجودی که این روش‌ها می‌توانند کنترل مداومی را ارائه دهند، اغلب با محدودیت‌هایی از جمله نگرانی‌های زیستمحیطی، توسعه مقاومت به نماتد و آسیب بالقوه به موجودات غیرهدف مواجه هستند. لذا، این مطالعه با هدف روشن کردن پیچیدگی‌ها و سازوکارهای مدیریت تلفیقی آفات (IPM) به عنوان بخشی از تغییر الگو به سمت مدیریت پایدار تلفیقی (ISM) تدوین شده است. ISM پیچیدگی‌های جوامع نماتد و تعاملات آن‌ها با اکوسیستم خاک را تصدیق می‌کند. این رویکرد جامع بر استفاده از استراتژی‌های مکمل-مانند عوامل کنترل زیستی، شیوه‌های زراعی (از جمله تناوب زراعی و گیاهان پوششی) و مقاومت گیاه میزبان-به شیوه‌ای هم‌افزایی تأکید دارد. این رویکرد جامع با هدف سرکوب طبیعی جمعیت PPN، به حداقل رساندن وابستگی به مداخلات شیمیایی و ارتقای سلامت بلندمدت خاک انجام می‌شود. به علاوه، این مطالعه به بررسی پیشنهادها برنامه‌ای خاص می‌پردازد که نمونه‌ای از این رویکرد ISM هستند و به پرورش‌دهندگان انار راه‌حل‌های عملی برای دستیابی به تولید پایدار و سودآور در عین حفظ رفاه محیط زیست ارائه می‌دهند. این مقاله با حمایت از تغییر به سمت ISM، قصد دارد به آینده‌ای مقاوم‌تر و پایدارتر برای کشت انار و شیوه‌های کشاورزی گسترده‌تر کمک کند.

واژگان کلیدی: کنترل PPN ها، فیتونماتدها، مدیریت تلفیقی آفات، کشاورزی پایدار