Abd-Elgawad *Egyptian Journal of Biological Pest Control* (2020) 30:58
https://doi.org/10.1186/s41938-020-00252-x

Egyptian Journal of
Biological Pest Control

REVIEW ARTICLE | Open Access

Optimizing biological control agents for controlling nematodes of tomato in Egypt

Mahfouz M. M. Abd-Elgawad

Abstract

Tomato is a major vegetable crop in Egypt and worldwide. Yet, many plant-parasitic nematodes (PPNs), especially *Meloidogyne* spp. and *Rotylenchulus reniformis* are a devastating threat to tomato cultivation in Egypt. This review addresses their biology, ecology, and economic importance from the standpoint of pest management. Soil treatment with synthetic nematicides has given some protection and enhanced tomato yields, but health hazards and environmental pollution are obstructing their intensive use. Moreover, some of such nematicides are being banned from the market. Therefore, safe biological control agents (BCAs) and their bioactive compounds should better be researched and developed to effectively replace hazardous nematicides. Abamectin, produced during the fermentation process of the actinomycete *Streptomyces avermitilis*, is recommended to manage PPNs of tomato in Egypt but further exploration should allocate where BCAs can reliably act with other agricultural inputs. Examples are given herein to streamline their development via synergistic interaction with compatible inputs such as chemicals and organic manure. Moreover, optimizing their delivery, interaction, and persistence under field conditions through novel ways such as the use of endophytic fungi and bacteria as well as bioactive molecules/nano-particles that have systemic activity in the nematode-infected plants should further be investigated and broadly disseminated.

Keywords: Nematodes, Tomato, Biological control, Bionematicides, Integrated pest management

Background

Tomatoes are considered the mother of vegetables because they are often found with or within any cooking in Egypt and many other countries. Moreover, it takes first rank among the vegetables as a processed crop (Kessel 2003). Therefore, tomato grows on a garden basis as well as under protected and field conditions. The commercial tomato (*Solanum lycopersicum*) belongs to the family of Solanaceae, a vegetable crop with savory taste and very important in human nutrition. It is used for fresh consumption and/or for the production of pastes, puree, ketchups, and fruit drinks (Ogwulumba and Ogwulumba 2018). Hence, tomato is cultivated in different seasonal plantations along the year in Egypt as one of the most important vegetable crops that can provide high incomes to both small and large scale growers compared to other vegetable crops.

However, tomato plants are more susceptible to several biotic stresses than other vegetables and cereals. Among the different biotic stresses, a group of the most famous and widespread pests is the plant-parasitic nematodes (PPNs), which can cause considerable damage to the tomato yield. Abd-Elgawad (2014) estimated annual yield losses of tomato due to damage by PPNs in Egypt as 1168779.5 metric tons of actual annual yield loss in 2012. Yet, PPN populations may affect tomato yields differently according to their species and levels as well as biotic and abiotic factors associated with the cultivated tomato. Specific examples of such yield loss figures that may reflect the reality of the situation and may be of use for locally oriented purposes were 2–3% in Florida and 15%, in California, USA, but it was 20–80% in Egypt (Abd-Elgawad and Askary 2015). So, reductions in tomato yield can be extensive but vary significantly

Correspondence: mahfouzian2000@yahoo.com
Plant Pathology Department, National Research Centre, El-Behooth St., Dokki, Giza 12622, Egypt

according to the interaction between plant and nematode species in the presence of other relevant factors. In addition to the direct crop damage caused by PPNs, many of the nematode species have also been shown to predispose tomato plants to infection by bacterial or fungal pathogens or to transmit virus diseases, which aggravate plant health and contribute to more yield losses (Noling 2019).

Several studies reported the occurrence of plant-parasitic nematodes in tomato fields (e.g., Mostafa et al. 1997; Abd-Elgawad and Aboul-Eid 2001). Ibrahim (2006) compiled the following PPN genera (with related species) from tomato fields: *Helicotylenchus* (*H. digonicus*, *H. cavenessi*, *H. microlobus*, *H. pseudorobustus*, *H. varicaudatus*), *Hoplolaimus* (*H. indicus*, *H. tylenchiformis*), *Meloidogyne* (*M. incognita*, *M. javanica*, *M. arenaria*, *M. ethiopica*, *M. hapla*, *M. acronea*), *Nacobbus aberrans*, *Pratylenchus* (*P. brachyurus*, *P. coffeae*, *P. jordanensis*, *P. penetrans*, *P. pratensis*, *P. scribneri*, *P. thornei*, *P. vulnus*, *P. zeae*), *Rotylenchulus reniformis*, *Trichodorus* (*T. allius*, *T. christiei*, *T. minor*), *Tylenchorhynchus* (*T. claytoni*, *T. cylindricus*, *T. capitatus*), and *Xiphinema americanum*. The life cycle of most PPNs comprises the following: the egg, four larval stages, and adult male and female. The first molt of the first larval stage occurs within the egg, which hatches to the second stage (juveniles) to find and infect plant roots or in some cases foliar tissues. Host searching or moving in soil happens within films of water around soil particles and root surfaces. Nematode feeding, usually takes place along the root surface. Generally, PPNs may be classified as migratory endoparasites (e.g., lesion nematodes, *Pratylenchus* spp.), semi-endoparasites (e.g., reniform nematodes, *Rotylenchulus* spp.), sedentary endoparasites (e.g., root-knot nematodes (RKNs), *Meloidogyne* spp.), and ectoparasitic nematodes (e.g., spiral and stunt nematodes, *Helicotylenchus* and *Tylenchorhynchus* spp., respectively). For most species of nematodes, as many as 50–100 eggs are produced per female, while in others such as the root-knot nematodes, up to 2000 may be produced. Under adequate ecological conditions, the eggs hatch and the emerging juveniles complete the life cycle within 4 to 8 weeks depending on temperature. Nematode development is often fast at optimal soil temperature 21.1–26.7 °C (Noling 2019).

Following are the most important and common PPN species of tomato cultivated in Egypt:

PPNs of tomato in Egypt

Root-knot nematodes (Meloidogyne spp.)

Meloidogyne spp. are obligate endoparasites of crop roots. One of the important factors that increases seriousness of this nematodes' group is its wide host range, which limits the availability of resistant/immune cultivars in crop rotations. Its broad host range includes dicotyledonous, monocotyledonous, herbaceous, and woody plants. The nematode genus comprises more than 90 species, with some species having several races. Four species (*M. javanica*, *M. arenaria*, *M. incognita*, and *M. hapla*) are universally major pests, additional seven being significant on a regional or local basis (Moens et al. 2009).

Meloidogyne spp. represent a main constraint, especially for horizontal expansion of agricultural production in Egypt, since these species are favored by light and sandy soils where reclaimed desert lands offer optimum conditions for their development and reproduction. Therefore, *Meloidogyne* spp. were the most prevalent and dominant PPN genus associated with numerous host plants in Egypt (Ibrahim et al. 2010; Abd-Elgawad 2019a), with 62.5% frequency of occurrence. *Meloidogyne* spp. were found in 96.26% of the surveyed fields in reclaimed lands (Bakr et al. 2011) that are conceivably cultivated with horticultural crops such as tomato. The survey represented different categories of light soils, i.e., Minufiya (El-Sadat), El-Beheira (El-Tahrir), and Sharkiya (El-Salhiya) governorates. Additionally, RKNs were more prevalent in samples collected from Beer El-Abd, Sahl El-Teina, and El-Sheikh Zowaiid with the percentage frequency of 48.1, 27.6, and 33.3%, respectively (Korayem et al. 2014). Admittedly, RKN population densities may considerably vary from one field to another based on nematode control tactics and strategies as well as cultural practices, biological, and edaphic factors.

Clearly, PPNs have often clumped or aggregated distribution in Egypt (Abd-Elgawad 1992; Abd-Elgawad and Hasabo 1995, and Abd-Elgawad 2016a) and worldwide (Duncan and Phillips 2009; Abd-Elgawad and Askary 2015), in general. Therefore, symptoms of RKN infection tend to occur in more or less definite areas, where tomato seedlings fail to develop normally. Plants displaying dwarfing or decline symptoms often happen in aggregations of non-uniform growth rather than as an overall damage of tomato plants within the whole field (Fig. 1). Unless a suitable nematode control measure is followed, a field infested with RKNs, or the like nematode pests, which has only a few such patchy areas at the transplanting time may then increase in size and number until the whole tomato cultivated area will be approximately infested. As with other PPNs, the general symptoms of nematode injury on tomato are to cause both dwarfing and decreasing in plant growth parameters, followed by/accompanied with yield loss. The magnitude of such symptoms is relevant to initial RKN population density and the rate to which population grows in reaction to the infested plants during the growing season. Tomato plants infested by the nematodes are usually more damaged by weeds than those without nematode

Fig. 1 A tomato field showing patchy area due to root-knot nematode (*Meloidogyne* spp.) infestation

injury. This is simply because these plants are less able to compete with weeds or even any other stresses than they should be. Factually, such symptoms are mostly the result of improper water supply or mineral nutrition to the tops. Consequently, the infected plants display slow recovery to improved soil moisture conditions, premature wilting, leaf chlorosis/yellowing, and other symptoms characteristic of nutrient deficiency. Strikingly, contrary to most PPNs, feeding by RKNs induces distinguished knot-like swellings (called galls) on the roots (Fig. 2) as a result of giant cell formation induced by the nematodes within plant roots. When plants are severely infected by RKNs, the normal root system is reduced to a limited number of severely RKN-galled roots with a completely disorganized vascular system. The RKN-infected roots are seriously hampered in their main functions of uptake and transport of water and nutrients. At season-end, the plants do not flower properly and therefore produce fruits of poor quality, and they are very easy getting drought damage. Rootlets are almost completely absent at severe infestation which may render plant death. Existence of other subterranean pests and/or pathogens may extend plant injury by damaging more roots. An enhanced production of ethylene, thought to be mostly responsible for symptom expression in tomato, has been shown to be tightly associated with RKN-root infection and gall formation (Noling 2019). Symptoms of plant damage appear based on

Fig. 2 Close-up view of root-knot nematode (*Meloidogyne* spp.) inducing different gall sizes of tomato roots

nematode population level, the degree of host suitability, and predominant biological and environmental conditions. New roots are often killed by severe infestations of RKNs, which may lead to plant death, especially in early growth stage. Older transplants, unlike direct seed, may tolerate relatively high initial population densities. The size of RKN gall may range from a few globe-shaped swellings to extensive areas of elongated, tumorous swellings (Fig. 2), which come out from multiple and frequent infections. Such galls are always used as a positive diagnostic confirmation of RKN presence and potential for crop damage.

Losses in tomato yield are usually directly related to pre-plant infestation densities in soil and/or previous crop roots. Such losses increase as infestation levels rise. Action thresholds necessitate RKN control if any individual of *Meloidogyne* spp. was found per 100 cm^3 of tomato-planted soil in Egypt and elsewhere (Abd-Elgawad and Askary 2015). This pre-plant threshold may not be used on established plants. Hence, the mere existence of RKNs suggests a potentially serious problem, especially on sandy soil during warm seasons, which favor a high RKN activity and reproduction.

Reniform nematode (Rotylenchulus reniformis)

The genus *Rotylenchulus* comprises ten species, but *R. reniformis* is the only species of major economic importance to agriculture in Egypt and worldwide (Robinson et al. 1997). This does not exclude that it is quite possible to detect other *Rotylenchulus* species from Egyptian fauna in the near future. This species is obligate semi-endoparasite (partially inside roots) on the roots of many plants that include fruit trees, vegetables, and field crops. A list of hosts including 314 plant species as well as no hosts for *R. reniformis* was published by Robinson et al. (1997). Among them, tomato is an excellent host and significant reductions in tomato growth parameters and yields were attributed to this nematode (Rebois et al. 1973; Nikman and Dbawan 2003, and Zhang et al. 2019).

Usually, the immature female penetrates the root using stylet secretions (Dropkin 1980). Like, RKNs, some *R. reniformis* populations can reproduce parthenogenetically (males are not required for fertilization). Its life cycle is usually shorter than 3 weeks when warm seasons expedite its reproduction. Moreover, it can survive for 2 years or more in the absence of its host in dry soil. In response to such an adverse environmental condition, *R. reniformis* enters a dormant state induced by drought in which the nematode becomes almost completely dehydrated and reduces its metabolic activity to an imperceptible level, a case called anhydrobiosis that enables the nematodes to live without water for extended periods of time (Radewald and Takeshita 1964; Wang 2019). Only females infect plant roots. The nematode initiates a feeding site in the pericycle and endodermal cells composing syncytial cells. A syncytial cell is a multinucleated cell formed via cell wall dissolution of several surrounding cells.

General symptoms of nematode infection are similar to those of water and nutrient deficiencies. Upon nematode infection and feeding, root development slows and secondary root growth is reduced. Consequent shoot growth suppression and reduction of tomato fruit quality occur. Additional infection by fungal and bacterial pathogens, following nematode infection can deteriorate plant health and contribute to root decay. Similar to RKN, *R. reniformis* has sexual dimorphism and economic threshold requires nematode control if any individual of *R. reniformis* is found per 100 cm^3 of tomato-planted soil (Abd-Elgawad and Askary 2015). Yet, host plants other than tomato, different *R. reniformis* populations, biological and edaphic factors may modify the threshold or economic injury level across the nematode's geographic distribution (Wang 2019).

Other plant-parasitic nematodes

Some of the abovementioned PPNs (Ibrahim 2006) have apparently been less recognized concerning their economic importance and deserve further studies in Egypt. These comprise species related especially to nematode genera *Pratylenchus*, *Hoplolaimus*, *Trichodorus*, *Xiphinema*, *Longidorus*, and *Tylenchorhynchus*. They are frequently found in tomato fields in Egypt but in low population densities and frequency of occurrence. So, future studies on one or more of these species/genera may investigate whether they have pathogenic significance and define their exact impact on tomato plants in Egypt. On the other hand, the importance of other species/genera has been documented elsewhere. For instance, the most prevalent and economically significant nematode species are the root-knot nematode, *Meloidogyne* spp., and sting nematode, *Belonolaimus longicaudatus* in Florida, USA (Noling 2019). Consequently, action thresholds recommended applying control measures if any individual of sting, stubby-root, reniform, or root-knot nematodes was detected per 100 cm^3 of tomato-planted soil in Egypt and elsewhere. These thresholds are 10, 40, and 80 nematodes per 100 cm^3 for awl (*Dolichodorus* spp.), lesion (*Pratylenchus* spp.), and sheath (*Hemicycliophora* spp.) nematodes, respectively (Abd-Elgawad and Askary 2015).

General approaches for management of tomato nematodes in Egypt

Certain tomato cultivars are resistant to the most common and damaging species of root-knot nematodes (Roberts and Thomason 1986; Bhavana et al. 2019) and *R. reniformis* (MacGowan 1977; Balasubramanian and Ramakrishnan 1983). Any tomato cultivars with the code

VFN (Verticillium, Fusarium, Nematodes) on the seed container are resistant to common RKN species. Hence, crop sequence with resistant/immune plant species/cultivars is recommended though further selection for fruit quality and yield to produce high yielding resistant tomato hybrids is still needed. That is simply because resistant cultivars often have low yield or quality traits, undesirable maturation times, or other specific problems (Roberts 1992). Therefore, further studies are in progress to identify better resistance sources under controlled conditions and compare molecular markers for efficient and rapid screening of RKN resistance in tomato. In this respect, recently identified genotypes may be used further in nematode resistance breeding programs of tomato where the Mi23 marker can be utilized for swift and efficient screening of the germplasm (Bhavana et al. 2019). In susceptible cultivars, chemical control via various synthetic nematicides is one of the most common management practices in Egypt. The Egyptian Ministry of Agriculture recommended such nematicides as oxamyl (Oxanem 24% SL, Vydate 10% GR, and 24% SL), cadusafos (Rugby 10 G), ethoprophos (Nemacap 20% EC), fenamiphos (Dento 40% EC, Fenatode 10% GR), and fosthiazate (Nemathorin 10% GR) to control RKNs infecting tomato roots (Anonymous 2018). Applying these chemicals at tomato nursery, protected cultivation and open field can give some nematode control and enhance tomato yields. However, due to risks of possible health hazards and environmental pollution by chemical nematicides, biological control tactics should be developed as a key element in integrated management programs of tomato pests and pathogens. Moreover, a few synthetic nematicides such as fenamiphos were deregistered for use, while the efficacy and profitability of the other available nematicides vary widely (Abd-Elgawad 2008; Verdejo-Lucas and McKenry 2014). On the other hand, in Egypt, there are many biological control agents, which are being produced by both governmental and private sectors and/or are in the production pipeline to be swiftly available. Conscious cultural practices should increase utilization of such local commercial products to manage PPNs (Abd-Elgawad and Askary 2020). Fortunately, some of these products are quite available and not expensive in Egypt (Table 1). Moreover, cultural practices such as crop rotation and intercropping, particularly with non-host/resistant plants, are utilized to reduce PPN population levels, improve soil, and increase antagonistic microorganisms (Wang 2019; Abd-Elgawad 2020a).

State of Egyptian tomato relevant to BCAs and pest management

Noling (2019) reported that effective, commercial biological control agents that can be prosperously utilized to control PPNs on some solanaceous crops such as tomato in Florida, USA, are not available. Apparently, this is basically related to the attributes of bionematicides which have relegated them to niche products, exclusively for high-value crops. In Egypt, however, tomato is sometimes considered among high-value crops. Factually, such a crop becomes of low value when prices drop because of oversupply, a case that occurs in frequent seasons, where tomato acreage is relatively large and/or environmental and biotic factors become favorable for high tomato yield. What are the basic facts that will debunk "high value tomato crop in Egypt?" It is tomato productivity and price that pose the produce as high- or low-value crop from one season to another. Markets and costs are important as well, especially when tomato is overpriced, but these are not the focus of this professional review. Yet, a meta-analysis study of such factors may also indicate research priorities and timing of utilizing bionematicides in Egyptian sustainable cultivation of tomato. Preferably, given the fact that biocontrol agents are mostly unable to penetrate beyond niche markets, tomato pests should be controlled biologically as best we can under such Egyptian conditions.

Table 1 Key commercially available bionematicides and chemical nematicides, their applications rates, and prices in Egypt*

Active ingredient	Product name	Application rate (product/feddan^{-1})$^{+}$	Price per feddan
Abamectin produced during the fermentation process of *Streptomyces avermitilis* (soluble concentrate at 20 g/l)	Tervigo 2% SC	2.5 l/Feddan	L.E. 2000 ($ 134)
10^9 CFU/ml of *Serratia* sp., *Pseudomonas* sp., *Azotobacter* sp., *Bacillus circulans*, and *B. thuringiensis*	Micronema	30 l/feddan (thrice)/year	L.E. 600 ($ 40)
10^8 units/ml *Purpureocillium lilacinus*	Bio-Nematon	2 l/feddan/year	L.E. 500 ($ 33)
10^9 bacterium cells of *Serratia marcescens*/ml water	Nemaless	10 l/feddan (thrice)/year	L.E. 600 ($ 40)
Cadusafos (O-ethyl S,S-bis (1-methylpropyl) phosphorodithioate)	Rugby 10 G	24 Kg/feddan	L.E. 6480 ($ 432)
Oxamyl (methyl 2-(dimethylamino)-*N*-(methylcarbamoyloxy)-2 oxoethanimidothioate)	Vydate 24% SL	4 l/feddan (twice)/year	L.E. 2800 ($ 187)

*There are broad host range claims by the manufacturer's product labels which have not necessarily been confirmed in independent trials
+Figures given for comparative purposes when products are uniformly applied to the soil (except oxamyl for foliar application too). For some products and other, including low value, crops, product may be incorporated into field soil, potting mix, or applied in greenhouses for which different rates apply (Wilson and Jackson 2013; Hammam et al. 2016)

Egyptian tomato used to be planted in three main seasonal plantations: summer, autumn, (Nili) and winter. Recently, in order to avoid shortage in tomato yield at definite periods of the year, additional planting seasons were introduced such as early and late summer plantations. Yet, each season has definite attributes of tomato cultivation (Mohamed 2000). For example, in late summer plantation (planted in March–May), the yield is relatively low because of high temperature during flowering and early fruit set, which causes flowers and small fruits to dramatically fall. Planting in autumn (June–August) also has reduced yield due to death of many seedlings by high temperature and the high activity and attack of whitefly *Bemisia tabaci* (Genn.) (Homoptera: Aleyrodidae). In this concern, crop rotation, which includes resistant tomato varieties, is an important tactic for managing RKNs, especially the three common species in Egypt, *Meloidogyne incognita*, *M. arenaria*, and *M. javanica.* However, the resistance has often failed as a result of the heat instability or high temperature. It has been demonstrated that threshold soil temperatures and incremental reductions in nematode resistance occur with each degree above 25.6 °C, such that at 32.8 °C tomato plants are fully susceptible to RKN infection (Noling 2019). On the contrary, low temperature may also lead to faint pollination and fertilization of the growing tomato plants with consequent low fruit set and yield in winter plantation (planted in September–November). Also, tomato is planted in both old Nile valley (clay or heavy soil) and reclaimed land (sandy or salty soil). Since RKNs thrive in light soils, it is quite possible to determine areas in which RKNs are likely to be a hazard to crop production (Taylor and Sasser 1978).

Precautions and considerations for the biocontrol of tomato nematodes

The current literature on research and illustrations of utilizing biological control agents (BCAs) and/or their active compounds to control the abovementioned PPNs on tomato in Egypt is really impressive and promising (Mostafa et al. 1997; Radwan et al. 2012; Basyony and Abo-Zaid 2018, and El-Ashry et al. 2018), but relatively incomplete in their economic analyses and cost-related issues of their mass production, delivery, and application (Abd-Elgawad and Askary 2018 and 2020). Indeed, biological nematicides based on living microbes and/or their bioactive compounds should become an important component of environmentally friendly pest managements systems (Davies and Spiegel 2011; Wilson and Jackson 2013; Abd-Elgawad and Askary 2018, and Abd-Elgawad 2020a). The high cost of discovering, developing, and registering new synthetic nematicides and the emergence of resistance-breaking nematode pathotypes have also contributed to increased interest with consequently more research on safe and effective biopesticides (Glare et al. 2012; Abd-Elgawad 2020a). In this respect, several Egyptian companies and governmental bodies have produced numerous bionematicides, which are less expensive than chemical nematicides. For example, cadusafos and oxamyl are more costly than their corresponding bionematicides (Table 1). Yet, reliable biocontrol tactics should consider holistic grasping of soil biological and ecological factors. Understanding nematode interactions that lead to their optimum management should be investigated via the multidisciplinary efforts to examine such interactions from the molecular to the ecosystem level. Hence, soil and root sampling should be a pre-consideration. Adequate sampling time, method, and process (Duncan and Phillips 2009) are necessary to detect and diagnose nematode problems, if any, via proper collection of relevant soil and root tissues whereas rational sampling can maximize isolation and fix distribution measure of the targeted BCAs (Abd-Elgawad 2020b). For instance, advisory sampling should be before tomato planting. It should predict the risk of nematode injury to a newly planted/transplanted tomato to allow for skillful harnessing of PPN management if so required. Nematode sampling at season-end, when PPNs are most abundant and easiest to detect, is best done before destruction of the previous crop.

Admittedly, the wide interest in BCAs as safe alternatives to synthetic chemicals has led to numerous developments in the commercialization of many bionematicides. Such developments should wisely cover all stages associated with the products of biocontrol agents starting from the surveys to explore a potential BCA and goes through its tests of efficacy under different laboratory, greenhouse, and field conditions and ending with inexpensive and reliable mass-production method, appropriate formulation, and packaging of this BCA to match the targeted nematode pest.

Although bionematicides are likely to become an increasing component in pest management systems, they are slower acting, less effective, and more inconsistent than control normally achieved with chemicals. In contrast, changes in political and social attitudes towards safer, more environmentally friendly compatible PPN control alternatives have increased opportunities for bionematicides, but this alone is insufficient to drive major changes in adopting their commercial application. In this respect, reliable, low risk, and environmentally sustainable phytonematode management solutions are critical to meeting producer, consumer, and regulatory needs. Mainly, relatively low efficacy and high costs have prevented numerous consumers from adopting and applying biopesticides. Recently, Abd-Elgawad and Askary (2020) reported the headlines currently considered affecting transmission success of these BCAs so that their utilization must be a way forward in crop protection/pest management. Such topics comprised optimized sampling, comprehending BCAs interactions with soil ecology and biota, cost-effective utilization of BCAs, genetic manipulation for enhanced PPN control, grower acceptance, and farmer awareness-raising of BCA merits and techniques of application.

Recommended biological control of tomato nematodes in Egypt

The only bionematicide that is produced by a living organism and recommended by the Egyptian Ministry of Agriculture is abamectin (Tervigo 2% SC). It is marketed by Syngenta Company. Abamectin is created during the fermentation process of the actinomycete *Streptomyces avermitilis* (Wilson and Jackson 2013). The active ingredient is abamectin (20 g/l). Its unique chelated formulation secures effective protection of the active ingredient for direct contact with PPNs and best soil penetration. The iron chelate can supply a micronutrient iron (Fe), which enhances soil fertility and health by increasing cation exchange capacity, raises chlorophyll content, and promotes root mass. The abamectin consists of 80% or more of avermectin B_{1a} and 20% or less of avermectin B_{1b}. So, abamectin is also called avermectin B_1 (Fisher and Mrozik 1989). It can block the transmission of electrical activity in invertebrate nerve and muscle cells mostly by enhancing the effects of glutamate at the invertebrate-specific glutamate-gated chloride channel with minor effects on gamma-aminobutyric acid receptors (Bloomquist 2003). Such a mechanism of action causes an influx of chloride ions into the cells, leading to hyperpolarization and subsequent paralysis of invertebrate neuromuscular systems. The product has strong activity against numerous genera of PPNs (Anonymous 2020). These included the root-knot, the dagger, the lance, the sting, the stubby-root, the lesion, the needle, the ring, the spiral, and the stunt nematodes. Its soluble concentrate (SC) formulation is a solid active ingredient dispersed in water. Such a formulation is favorable due to merits such as effectiveness, ease of use, and absence of dust when compared to formulation types such as wettable powder and emulsifiable concentrate formulations. Within the soil, abamectin acts mainly by contact activity. The recommended rate, by the Egyptian Ministry of Agriculture, of its application is 2.5 l/feddan (Anonymous 2018).

Suggestions for optimizing biological control of tomato nematodes in Egypt

Surely, the abovementioned attributes of bionematicides entail their development with skillful application in order to be more effective and more economical. Therefore, the following requirements should be sought to fulfill their full potential:

(I) Integrated management of tomato nematodes

Although resistant tomato varieties, crop rotation, and/or intercropping can sometimes be effectively utilized in integrated pest management (IPM) for PPN control, additional ones should be sought. Plasticulture technologies proved effective against PPNs in Egypt. The best decrease in RKN populations occurred in transparent sheet compared to the other colors (Bakr et al. 2013). Tomato growth parameters were considerably increased in different color sheets as well. Bionematicides should further be tested to act synergistically or additively with such other agricultural inputs in IPM programs (Abd-Elgawad and Askary 2018; Abd-Elgawad 2019b). For example, shoot dry weight of tomato had better ($P \leq 0.05$) increase, when *Pseudomonas fluorescens* GRP3 was combined with organic manure for the management of *Meloidogyne incognita* than using either *P. fluorescens* or organic manure alone (Siddiqui et al. 2001).

Hence, multiple and further techniques for various combinations of different components for effective IPM programs should be explored. These may include agrotechnical approaches, e.g., solarization and soil aeration, adding soil amendments including various green manures and composts, resistant and tolerant cultivars, crop rotation, or and/or pesticides and/or pesticides (e.g., Abd-Elgawad et al. 2016; Kepenekci et al. 2017 and Abd-Elgawad and Askary 2018). Abd-Elgawad et al. 2019). For this latter, Dahlin et al. (2019) found that the combination of a chemical pesticide (fluopyram which has reduced ecotoxicological profiles) to downregulate the *M. incognita* population on tomato, followed by the application of a fungal antagonist (*Purpureocillium lilacinum* strain 251) was more successful to control the nematode and increase yields than each treatment alone. Such integrated biological and chemical strategies should become an important component to manage *Meloidogyne* spp. and other plant parasitic nematodes in the future. Moreover, other combinations to control PPNs should be tested and utilized as integrated method and additional option rather than as a onetime solution. Besides the nematode controlling capacity, the profit of the additional application should be counted and precisely evaluated for the particular market. In regards to the chemicals and their residual effects as reported for fluopyram, pre-harvest losses could be overcome by alternative biological or chemical treatments to downregulate *Meloidogyne* spp. population on tomato to give *P. lilacinum* 251 or a different BCA the potential to suppress PPN populations during the entire period of tomato growth. Consolidated utilization of bionematicides and other pesticides/agricultural inputs should be practiced on a wider basis. Hence, novel tactics should be employed not only to incorporate BCA synergistically or additively with favorable inputs but also to broadly disseminate such a consolidated option for authentic penetration of pesticide markets. Eventually, this tactful utilization of BCAs should be based on relevant sound knowledge, i.e., pathogenicity of the targeted species, their ecology, biology, and natural enemies, and perfect grasping of the related edaphic factors which may interact with each other and with the host plants (Abd-Elgawad 2016a, 2016b; Barker et al. 2020).

(II) Upgrade their delivery methods and field persistence

General upgrading of biological control of pests should wisely cover the areas of product activity, delivery, persistence, and application. However, most investigations address product activity, especially new isolate/BCA selection as bionematicides. For tomato nematodes, many isolates were detected with promising biological control potential in Egypt (Abd-Elgawad and Kabeil 2012; Radwan et al. 2012; Basyony and Abo-Zaid 2018; El-Ashry et al. 2018; Abd-Elgawad and Askary 2018, and Shehata et al. 2019). Clearly, the scopes that will supply transformational shift are in optimizing their delivery and persistence under actual/field conditions. New approaches including the use of endophytic microorganisms such as fungi (Abd-Elgawad and Kabeil 2010; Schouten 2016) and bacteria (Abd-Elgawad 2016a; Tran et al. 2019) as well as bioactive molecules/nano-particles (Jang et al. 2016; Nour El-Deen and El-Deeb 2018, and El-Sherif et al. 2019) that have systemic activity in RKN-infected plants should further be investigated and broadly disseminated. Also, specific delivery techniques of certain BCAs to target tomato nematodes should be researched. In this respect, controlling RKN on tomato was more effective, when the seedling roots were dipped in the *Pseudomonas fluorescens* broth for 30 mi than similar dipping in 1% carbofuran as chemical nematicide (Thiyagarajan and Hari 2014). Such a method promoted both delivery and persistence of *P. fluorescens* in soil to suppress the pest. Clearly, bionematicide persistence at the site of PPN occurrence in the rhizosphere is essential.

(III) Further investigations on the chemistry of bioactive from BCAs

For example, the *Photorhabdus-Heterorhabditis* complex possesses virtually many attributes of an ideal biological control agent. This complex proved useful against both insect and nematode pests of tomato (e.g., Abd-Elgawad 2017a; El-Ashry et al. 2018). However, optimizing the interaction of the mutualistic bacteria *Photorhabdus* spp. with other biotic and abiotic factors for wise integration with other agricultural management techniques is still needed. Abd-Elgawad (2017b) addressed the molecular structures and events of *Photorhabdus* bacteria, which will promote our knowledge of genetic bases for a wide array of toxins and secondary metabolites responsible for nematicidal capacity. Hence, using *Photorhabdus* concentrated metabolites or bacterial broth treatments as well as their various identified active compounds to manage tomato nematodes should be examined. In this vein, transcinnamic acid was recorded to be a major compound in *P. luminescens*' suppressive activity against plant pathogens. Abd-Elgawad (2017b) stressed the need for field testing and economic feasibility study regardless of the type of treatment (bioactive chemicals, metabolites, and/or BCA treatments) as various biotic and abiotic factors may reduce the potency and longevity of such compounds. Eventually, such studies can develop more effective *Photorhabdus* biopesticides with promising molecular and biotechnological engineering prospects in the management of crop pests. This will lead to better grasping of their modes of action too. Moreover, whole or partial genome sequencing will be useful tools for selection of superior isolates with a known mode of action, such as the production of antibiotics or novel variations of toxins (Glare et al. 2012; Baiocchi et al. 2017).

(IV) Further roles to optimize management of tomato nematodes

Surely, other vital roles are necessary to optimize biocontrol agents and their relevant methods in order to better improve the management of PPNs in general (Davies and Spiegel 2011; Glare et al. 2012, and Abd-Elgawad 2020a) including tomato nematodes in Egypt. Abd-Elgawad (2016c) addressed several shortcomings in testing and applying BCAs against PPNs, where weak links in a nematode's life cycle that can be targeted for biocontrol by fungal or bacterial antagonists were illustrated in more details. The keys to advance biocontrol of PPN pests in Egypt will be increased academic-industry partnerships in addition to awareness-raising of more growers, cooperatives, and extensions of beneficial BCAs and relevant bioactive compounds. For this latter, a shift in mindset away from using the conventional chemical nematicides is needed.

Conclusions

Economically, tomato is a very important crop in Egypt and elsewhere. Therefore, PPNs of tomato should be managed by safe bionematicides in IPM programs to avoid health hazards and environmental pollution. This review suggested significant approaches for optimizing biological control of tomato nematodes in Egypt. Integrated management of tomato nematodes should include additional inputs with synergistic or additive interaction with the BCAs or their bioactive compound. Enhancing their delivery methods and field persistence should be followed, especially via recently utilized approaches. The chemistry of bioactive from BCAs should be further examined for widening in targeting specific pests. Several shortcomings in testing and applying BCAs against PPNs of tomato could be more adequately addressed.

Abbreviations

PPN: Plant-parasitic nematode; BCAs: Biological control agents; IPM: Integrated pest management

Acknowledgements

This study was supported in part by the NRC In-house project No. 12050105 entitled "Pesticide alternatives against soil-borne pathogens and pests attacking economically important solanaceous crops." The author is grateful to Dr. MMA Hammam for providing the figures. Facilities offered by The National Research Centre are appreciated.

Author's contributions

The author has developed and implemented this review article and written it. The author read and approved the final manuscript.

Funding

Financial support made by the National Research Centre, Egypt, is gratefully acknowledged.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

The author declares that he has no competing interests.

Received: 1 February 2020 Accepted: 16 April 2020
Published online: 13 May 2020

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