

REVIEW

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Biological control of nematodes infecting eggplant in Egypt

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Abstract

Background: Eggplant is of great renown in Egypt and worldwide as it is favorable and high value vegetable crop. Yet, many plant-parasitic nematodes (PPNs) can penetrate the roots of this plant and feed on it, causing heavy losses in its yield. *Meloidogyne* spp. (root-knot nematodes, RKNs) and *Rotylenchulus reniformis* rank high among these parasites in Egypt.

Main body of the abstract: This review compiles PPN ecology, biology and economic value from the pest management point of view. Applying production practices and other preventive methods against PPNs should be a priority. Accelerating and unprecedented public concern about excessive use of chemical nematicides leading to health problems, development of pest resistance, and environmental contamination, has boosted interest in developing eco-friendly biologicals as safe substitutional materials. Hence, safe biological control agents (BCAs) are reviewed herein to prove that they are quintessential to nematode control on eggplant in Egypt. Thus, BCAs should reliably operate with other agricultural inputs in integrated pest management programs against eggplant nematodes.

Short conclusion: A few paradigms are shown herein which foster BCA practical use via additive or synergistic relation with compatible inputs such as compost, chemicals, and manure. Upgrading their delivery techniques, beneficial interaction and persistence in fields with nematode-infected eggplants should be broadly tested and greatly disseminated.

Keywords: Biocontrol, Nematicides, Eggplant, Nematode management

Background

Solanum melongena L. (known as Bazingan in Egypt, aubergine in France and England, eggplant in the United States, and brinjal in India) is an economically important and popular vegetable crop in Egypt and elsewhere (Dau-nay 2008; Zayed et al. 2017). Its fruits range in size, shape and color depending on the varieties. The fruits may be black, purple, purple white, white, yellow or purple. Eggplant has two main groups: long (called Bride) and oval or spherical (called Romy). The fruit should be harvested as soon as it reaches maturity. Any delay in harvest time may increase the bitterness and seeds within the fruit, rendering inferior quality fruit (Zayed et al. 2017). The

plant flowers are hermaphrodite where self-pollination is made. Its fruits are eaten after cooking, boiling or grilling. The fruit is useful in the treatment of many diseases and the prevention of others (Zayed et al. 2017). Its fibers are stimulant for the intestine to help in the digestion process, expelling wastes, generating urine and cutting headache. Its crust contains vitamin B and C and trace amounts of calcium, iron and phosphorus in addition to flavonoids. Eggplants have plenty of fibers but low in soluble carbohydrates. As a regular food, eggplants back good blood circulation and pressure, reduce harmful cholesterol, guard the digestive tract, and assist to control diabetes (Zayed et al. 2017). According to the FAO in 2012, 90% of the eggplant yield is produced by five countries: China, India, Iran, Egypt and Turkey (Ismael et al. 2017). Eggplant is a warm-season vegetable but can grow in Egypt at different seasons; 35–60-day-old seedlings

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are transplanted early (in March) or late (April and May) in summer season, July and August (fall season), and November and December (winter season, under plastic tunnels). Harvest often occurs 65 to 80 days after transplanting, depending on the variety and temperature. When starting from seed, about 100–120 days are required to reach maturity. Eggplant is actually a perennial, but most people treat it as annual, because it is not frost tolerant. So, in the warm regions like Egypt, plants can keep up production but plants are sharply pruned after the harvest and kept alive till next March when they are fertilized for second season production (Zayed et al. 2017).

However, eggplants are generally so susceptible to some biotic stresses. Among such stresses, a variety of the most dominant and globally spread pests is the plant-parasitic nematodes (PPNs) which can reduce yield significantly. Detailed effect of soil fertility and pesticides on nematode activity, other microbiota, and its subsequent effect on crop yield was reported elsewhere (Abd-Elgawad and Mohamed 2006; Rahman et al. 2020). Abd-Elgawad (2014) assessed losses of eggplant yield due to damage by PPNs in Egypt as 20% of total annual yield which may translate into 298,410.5 metric tons of yield loss. However, PPN populations may damage eggplant yields in various settings differently according to the pathogenicity of PPN species, and the nematode density as well as the relevant interacting factors which impact the cultivated eggplant. Thus, accurate sampling approaches are required for precise and close quantification of these pests (Abd-Elgawad 2016a, b). A few PPN species have also proved to predispose eggplants to infection by fungal or bacterial pathogens or to transmit virus diseases, which usually aggravate losses of eggplant yield (Noling 2019).

Ibrahim (2006) reported the next PPN genera (and their related species) associated with eggplants as economically significant pests: *Helicotylenchus* (*H. dihystra*, *H. cavenessi*, *H. pseudorobustus*), *Meloidogyne* (*M. incognita*, *M. javanica*, *M. arenaria*), *Pratylenchus* (*P. brachyurus*, *P. jordanensis*, *P. penetrans*, *P. thornei*), *Rotylenchulus* (*R. reniformis*, *R. parvus*) and *Xiphinema americanum*. Generally, the life cycle of PPNs goes through bisexual adults, eggs, and four larval stages. Usually the second stage larvae or juveniles hatch to search and feed on plant roots or in some PPN species on foliar tissues. According to their feeding site and habitat, PPNs may be categorized as semi-endoparasites (e.g., reniform nematodes; *Rotylenchulus* spp.), migratory endoparasites (e.g., lesion nematodes; *Pratylenchus* spp.), sedentary endoparasites [e.g., root-knot nematodes (RKNs)]; *Meloidogyne* spp.), and ectoparasitic nematodes (e.g., spiral; *Helicotylenchus*). An average of about 50–100 eggs are

laid by a female, but serious genera as *Meloidogyne*, may lay up to 2000 eggs. The life cycle often lasts 4 to 8 weeks; usually relatively high temperature hasten the cycle duration where optimal soil temperature 21.1–26.7 °C (Noling 2019). Next are the most significant and prevalent PPN species of eggplant grown in Egypt:

Main text

PPNs of eggplant in Egypt

Root-knot nematodes (*Meloidogyne* spp.)

Nematode spread and distribution patterns These endoparasites have obligate feeding habit on crop roots. The nematode group is characterized by its broad host range that shackles the accessibility of resistant/immune cultivars in crop sequences. Such a wide range covers a wide variety of plants; not only woody and herbaceous plants, but generally monocotyledonous and dicotyledonous plants. Eggplants grafted on RKN-resistant rootstocks are sometimes used. Hence, nematode-resistant sources are still necessary for breeding programs given the fact that some related *Solanum* species such as *S. torvum* has high resistance level to *Meloidogyne* spp. (Daunay 2008; Öçal and Devran 2019; Gisbert et al. 2011). Also, eggplants were genetically engineered via the tomato Mi-1.2 gene and thus acquired resistance to *M. javanica* (Goggin et al. 2006). Papolu et al. (2016) suggested that cystatins can help in enhancing the eggplant resistance within a strategy that could eventually increase crop yield. Although this nematode group includes more than 90 species, only four species (*M. incognita*, *M. hapla*, *M. javanica*, and *M. arenaria*) are globally main pests; other seven species are serious from a regional or local scope (Moens et al. 2009).

Meloidogyne spp. perform a major obstacle especially for horizontal expansion of crop production including eggplant cultivation in Egypt, because these species thrive in light and sandy soils. Hence, reclaimed deserts present an optimum status for their establishment and multiplication (Abd-Elgawad 2020a). Consequently, RKNs are the most widespread and significant PPN genus damaging many plant species in Egypt. This genus recorded 62.5% frequency of occurrence (Ibrahim et al. 2010; Abd-Elgawad 2019a). Its species were detected in as many as 96.26% of the examined fields in such lands (Bakr et al. 2011). The fields are perceivably planted to field and horticultural crops, e.g., eggplant. This study covered various categories of reclaimed but light soils located at El-Beheira (El-Tahrir), Minufiya (El-Sadat), and Sharkiya (El-Salhiya) governorates. Also, RKNs were more dominant in agricultural soil of Sahl El-Teina, Beer El-Abd, and El-Sheikh Zowaiid with the percentage frequency of 27.6, 48.1, and 33.3%, respectively (Korayem et al. 2014). Clearly, densities of RKN population differed from one field to another as the nematodes were

subjected to various control methods and production practices, in addition to biological and physical factors.

Frequently, PPNs display clumped distribution in Egypt (Abd-Elgawad 1992; Abd-Elgawad and Hasabo 1995; Abd-Elgawad et al. 2016, a, b, c) and worldwide (Duncan and Phillips 2009; Abd-Elgawad and Askary 2015) in general. Therefore, patches of RKN infections possibly in scattered areas/sites of the field can be observed where eggplant seedlings fail to grow normally. So, weakening symptoms on stunted plants often occur in spots of non-even plant growth, i.e., non-uniform damage of eggplants over the whole planted area (Fig. 1). Nematodes spreading in these spots or patchy areas should be adequately managed at the season-start. If not, they may expand and develop in size of the infested field sites to cover almost all eggplant-cultivated fields.

RKN Pathology and losses Like other PPNs, the common symptoms of RKN injury on eggplant are stunted plants and decrease in their growth parameters which ultimately lead to considerable loss. The intensity of RKN disease symptoms is positively correlated with initial density of RKN populations and their reproduction capacity which depend on the biological and environmental factors during the plant growing season. Eggplants infected by RKNs are often more deteriorated by noxious weeds than plants without RKN infection. This is definitely because the plants cannot often stand for weed competition or any other stresses. Factually, plant weakness of infected plants is mostly due to insufficient mineral nutrition or water supply to the tops. Hence, the infected eggplants exhibit symptoms that are characteristic of nutrient deficiency such as leaf yellowing/chlorosis, slow response to adequate soil moisture conditions, and premature wilting. Unmistakably, RKNs infection and consequent feeding on plant roots will result in knot-like swellings known as nematode galls on the eggplant roots (Fig. 2) due to formation of giant cells inside the tissues of plant roots. When plants are harshly attacked and infected by RKNs, the intact root system is diminished to a confined volume of remarkably RKN-galled roots where the vascular system of the eggplant roots is greatly disorganized. Factually, eggplant growth reduction and loss in yield are correlated with nematode population density, the magnitude of host suitability, and the implemented control measures (e.g., Abd-Elgawad et al. 2019), as well as biological and ecological conditions. Eggplant roots may bear different numbers and sizes of RKN galls with different shapes and locations on the root system (Fig. 2).

Action thresholds necessitate RKN control for infected eggplants if a single nematode was detected per 100 cm³ of eggplant-cultivated soil in Egypt and other countries (Abd-Elgawad and Askary 2015). Therefore, promising

research results especially of RKN biocontrol on eggplant which will be presented herein should further be practiced on wider scale in Egypt.

Lesion nematodes (*Pratylenchus* spp.)

Pathogenicity In fact, the losses and prevailing distribution of RKNs often hide the role and losses of other PPN genera such as lesion nematodes, *Pratylenchus*, and reniform nematode, *Rotylenchulus* on eggplant. Clearly, *Pratylenchus* spp. have a broad host range feeding on most cultivated Various weed species also may back the nematode reproduction as suitable hosts. Admittedly, different species of *Pratylenchus* are associated with various crops, grasses, and weeds in Egyptian soils (Abd-Elgawad 2019a). Hence, it is quite possible to cultivate eggplant in the above-mentioned soils reported by Ibrahim (2006) to be infested with one or more of *Pratylenchus* spp. However, little information is available on the exact eggplant yield damage/loss by a definite *Pratylenchus* sp. in Egypt. Moreover, lesion nematodes can also predispose plants to invasion by some genera of soil borne pathogens in addition to their direct damage in parasitizing eggplants. For example, in steam-sterilized soil inoculated with *Verticillium alboatrum* and *Pratylenchus penetrans*, McKeen and Mountain (1960) demonstrated a synergistic relationship between *V. alboatrum* and *P. penetrans*. At low and intermediate levels of *Verticillium* inoculum, the nematode increased wilt may be a function of the number of nematodes present. Except at the high inoculum levels of *Verticillium*, significantly larger numbers of *P. penetrans* occurred in eggplant roots in the presence than in the absence of the fungus. On the other hand, Mizukubo (1995) tested the reproduction of three populations of *Pratylenchus coffeae* in Japan and proved the presence of physiological races among them on eggplant. Also, Di Vito et al. (2002) examined six population of *Pratylenchus* spp. from the Mediterranean region and found that eggplant was good host for *P. neglectus* but *P. pinguicaudatus* reproduced better on faba bean, lentil and pea than on eggplant. Machado and Inomoto (2001) used the nematode-reproduction factor or Rf [=the nematode-final population (Pf) divided by the nematode-initial population (Pi); or Rf = Pf/Pi] to examine host suitability of eggplants to *Pratylenchus brachyurus*. They reported that intermediate nematode populations occurred at 65 days after *P. brachyurus* inoculation (Pf/Pi = 2.78), but in Khan's (1992) study of the same crop, a strong population increase (Pf/Pi = 31.4 at 75 days after inoculation) was demonstrated.

Control measures *Pratylenchus* spp. should have a comprehensive control measures within integrated pest management (IPM) approach. A basic control measure in this

approach is to use nursery stock free from the nematodes. Also, rotating resistant plant cultivars/species such as pearl millet with susceptible eggplants could be utilized successfully in Egypt. Like other solanaceous crops such as tomato and pepper, chemical nematicides can effectively control PPNs on eggplant but their related health hazards, development of pest resistance, and environmental pollution should be avoided. Also, raising awareness of growers via guiding them to sound production exercises such as destruction of weeds and infected-plant residues in eggplant fields can upgrade nematode control (Abd-Elgawad 2019a, b).

Reniform nematode (*Rotylenchulus reniformis*)

Lone et al. (2014) stressed that *Rotylenchulus* with 10 species are prevalent and significant group of PPNs globally but often detected in tropical and subtropical climate. Among its species, *R. reniformis* with at least 314 plant host species is the most prominent and economically appreciated one (Robinson et al. 1997). Reniform nematodes rob nutrients of infected plants and reduce the quantity and quality of the eggplant fruits. Symptoms are primarily expressed as minimized root systems, nutrient deficiency, and stunting of the infected plants. Reduction in plant longevity negatively affects harvest duration. Economically appreciated management of reniform nematodes in view of their worldwide distribution and broad host range especially for *R. reniformis* has always been a dire need for growers globally (Lone et al. 2014).

The lifecycle of reniform nematode was recently reported (Abd-Elgawad 2020a). Its time span is frequently less than three weeks in warm regions. The nematode can survive for more than two years without its host under stressed condition, i.e., in dry soil. In such a case, *R. reniformis* can live in a dormant state stimulated by drought and the nematode is almost dehydrated with diminished metabolic activity; a condition called anhydrobiosis that helps *R. reniformis* to live without water for long time (Wang 2019). On infecting plant roots, the nematode female establishes a feeding site comprising syncytial cells.

Most manifestations and disease signs resulting from PPN infection are generally identical to those of lack in nutrients and eggplant irrigation. As *R. reniformis* feeds on the eggplant roots, the growth of the whole plant is decreased. Additional infection by other soil borne pathogens after *R. reniformis* establishment on eggplant roots can worsen plant status. Both *R. reniformis* and RKN have sexual dimorphism.

Other plant-parasitic nematodes

Additional PPNs have obviously been less recognized regarding their economic significance (Ibrahim 2006)

and are entitled to more investigations in Egypt. These include the nematodes in the genera *Xiphinema*, *Longidorus*, *Hoplolaimus*, *Paratrichodorus*, *Trichodorus*, and *Tylenchorhynchus*. They are frequently associated with eggplant roots in Egypt but in low frequency of occurrence and population densities. Therefore, further investigations on any of them may reveal whether they demonstrate economic importance and determine their damage on eggplants in Egypt.

Also, the significance of other nematodes on eggplants has been reported from other countries, e.g., *Belonolaimus longicaudatus* in Florida, USA (Noling 2019). Likewise, action thresholds are suggested for any detection of sting or stubby-root nematodes; usually in sample size of 100 cm³ soil of eggplant-planted field. The corresponding thresholds are 10, 40, and 80 nematodes for awl, stunt, and lesion nematodes, respectively (Abd-Elgawad and Askary 2015). Yet, further PPN species and additional relevant factors may alter the threshold from one location/season to another (Wang 2019).

Expertise for biocontrol of PPNs on eggplant

Application of microorganisms

Chubachi et al. (2003) found that *Streptomyces* sp. strain NA-369 can control *M. incognita* infecting eggplant. Significant reductions in the gall index of eggplants and advantageous changes in nematode population density and growth parameters of eggplants resulted from the strain NA-369 addition to amend the soil relative to the check area. Also, *Serratia marcescens*, ground ascaris (*Ascaris lumbricoides*) cuticle, two entomopathogenic nematode (EPN) species (*Heterorhabditis bacteriophora* strain EGG and *Steinernema carpocapsae* strain All, and garlic extract added to the soil singly, were tested to control *M. incognita* on eggplant in the glass-house (Abd-Elgawad and Mohamed 2006). These additions were also compared with the nematicide oxamyl. All the treatments fostered various parameters of plant growth but differently. El-Sherif et al. (2007) tested sesame-oil-cake, horse manure or *Bacillus thuringiensis* singly and/or incorporated with oxamyl on *M. incognita* infecting eggplant. All tested materials were obviously advantageous in terms of fostering plant growth and suppressing nematode population; *B. thuringiensis* as single addition or incorporated with oxamyl showed the best plant growth parameters. Incorporating horse manure with oxamyl seemed to be the best application in controlling *M. incognita* development and improving plant growth parameters.

Further integrated application

In a glasshouse experiment, Usman and Siddiqui (2012) tested *T. harzianum* and *Purpureocillium lilacinus* at the same time along with *M. incognita* on eggplant.

They found that these biocontrol agents were effective in suppressing *M. incognita* and could be used as safe agents for sustainable environment. Abolusoro et al. (2013) reported that organic manure (poultry, cow dung, domestic waste) and inorganic fertilizer (NPK 15:15:15) were effective in suppressing *M. incognita* soil and root populations, reducing gall index of the treated eggplants compared with the control in a greenhouse. Mokbel and Alharbi (2014) found that *Pseudomonas fluorescens*, *B. thuringiensis*, *Bacillus subtilis*, and *S. marcescens* each alone or in a combination resulted in 50.5–90.3% restrained *M. javanica* egg-hatch and J_2 activity and caused 56.5–86.8% decrease in egg-masses/eggplant root system, root galls, and 50.9–73.7% rise in the shoot and root dry weights of eggplant. Also, *Arthrobotrys conoides*, *Purpureocillium lilacinus*, *A. oligospora*, and *Saccharomyces cerevisiae* induced considerable reductions (69.5–89.5%) in galls and egg-masses/root system, and led to 53.7–60.9% enhancement in shoot and root dry weights of eggplant. The potency of *P. lilacinus* in colonizing *M. javanica* egg masses and eggs formed on eggplant roots ranged from 45.2 to 99.2%, relative to the untreated control. Lone et al. (2014) found that the simultaneous inoculation of *R. reniformis* with different inoculum levels of *Steinernema* sp. considerably decreased the injury resulted from *R. reniformis* infection. The best results were attributed to with the dose of 5000 infective juveniles of *Steinernema* sp./500 g soil. Abdellatif et al. (2016) tested the efficacy of green silver nanoparticles (GSN) of $AgNO_3$ dissolved in two separate algal (*Ulva lactuca* or *Turbinaria turbinata*) extract solution on reproduction parameters of *M. javanica* on eggplant. All treatments improved eggplants growth parameters but *U. lactuca* was more effective in reducing second-stage juveniles (J_2) of *M. javanica* (69%) population in soil. In pot experiment, Khushbu et al. (2016) found that soil application with *T. harzianum* at 3 g/kg soil was better than *T. viride* and *P. Fluorescens* at 3 g/kg soil in enhancing plant growth of brinjal and managing *M. incognita*. However, the chemical check carbofuran 3G at 2 kg a.i. per ha gave the best results. Gad and Sergany (2017) studied the effect of dried leaf powders of cabbage, sorrel, spinach, rocket and tomato compared to oxamyl on *M. incognita* infecting eggplant under greenhouse conditions. All treatments showed remarkable increase in plant growth parameters and reduced nematode criteria. Ismael et al. (2017) found that the Rf of *M. incognita* were 0 and 0.50 when plant extract mixture product (Nemakey) and Humic acid 15% were applied on eggplants, respectively. Humic acid had the highest no. of fruits /plant, while Nemakey had significant effects on increasing fruit weight (g), and yield (kg/plant). Deimi and Karami (2017) noted that drenching application of compost teas derived

from rice straw gave more ($P < 0.05$) fresh weight of eggplant infected with *M. javanica* or *R. reniformis* than those derived from rice hull, tomato, potato, citrus, guava and city waste compost. Zeerak et al. (2017) found that as endospore level of *Pasteuria* isolates PP-J and PP-3/ J_2 increased, the nematode development stages decreased. The two isolates of *Pasteuria penetrans* were remarkably effective though PP-3 was superior to the other one. Osman et al. (2018) used either single or combined treatments of *Trichoderma harzianum* filtrate, inorganic fertilizer, chicken manure, *Bacillus thuringiensis*, NPK, and Oxamyl for field control of both root rot disease and *M. incognita* infecting eggplant in Egypt. All such treatments had variable activities against the root rot disease incidence and *M. incognita* though enhanced the crop yield. The chicken manure had the best results but combined treatments were generally better than single treatments in increasing the eggplant yield. Abd-El-Khair et al. (2018) used *T. harzianum*, *T. virens* and the oil cakes of olive and castor bean alone or in combination for controlling *Fusarium solani* and *M. incognita* on eggplants in pots experiment. Either *Trichoderma* with any of oil cakes decreased root rot disease incidence, reduced nematode parameters (viz. J_2 in soil & roots and the numbers of galls & egg-masses), and enhanced the growth parameters of eggplants compared to the control in Egypt. Noweer and Elkelany (2019) used *Dactylaria brochopaga* as nematode-trapping fungus and *Verticillium chlamydosporium* mixed with molasses, yeast, and vermiculate to considerably suppress *M. incognita* infecting eggplant under field condition in Egypt. The data revealed that the weights of eggplant yield per plant were significantly enhanced due to *D. brochopaga* treatments relative to the check.

General approaches for management of PPNs infecting eggplant in Egypt

Strategies

Crop rotation with other resistant/immune plant species/cultivars should be practiced though eggplant-resistant cultivars are still desperately needed (Papolu et al. 2016 and Öçal and Devran 2019). More importantly, phytosanitary measures should be continuously practiced in eggplant fields to avoid their infestations by the nematodes especially in newly reclaimed areas with light soils where RKNs can readily thrive. In such areas, caution should be exercised, because the nematodes can attack cultivated area in the newly reclaimed land via infected or unhealthy seedlings, contaminated soil, organic fertilizers, machinery, plant materials, and irrigation which may contain the nematodes. For current susceptible eggplants, management via various chemical nematicides is so common control practice in Egypt. The Egyptian

Ministry of Agriculture recommended such nematicides as oxamyl (Oxanem 24% SL, Vydate 10% GR and 24% SL), Fenatode 10% GR), cadusafos (Rugby 10 G), fenamiphos (Dento 40% EC, ethoprophos (Nemacap 20% EC), and fosthiazate (Nemathorin 10% GR) to manage RKNs on solanaceous crops (Anonymous 2017). Such chemicals can give some nematode control and increase eggplant yields. Their possible combination and mode of application (granular, drenching etc.) has various effects on soil fauna and flora (Abd-Elgawad 2008; Meena et al 2020). Nonetheless, due to risks of expected health probability and ecological pollution by these chemicals, biocontrol methods should be advanced as an important device in IPM programs of eggplant noxious pathogens and pests.

Application of bioagents

Considering the various views of gaining in managing PPNs on eggplant using ecofriendly methods, functional sampling to enhance isolation of BCAs should be

practiced (Abd-Elgawad 2020b). Moreover, a few locally adapted bio-nematicides have been commercialized in Egypt (Table 1). Labels attached to the bio-nematicides may present the necessary instructions for their adequate storage and practical use. So, they should be followed. The effectiveness of such bionematicides on different nematodes is generally known to reduce their population levels to non-damaging ones. Clearly, production practices of eggplants should enhance both application of such local products and efficacy to control PPNs (Abd-Elgawad and Askary 2020). Identification of the major relevant bio-agents, their mass production, release method, mode of assessing effectiveness, interaction with other agricultural inputs, and effect in the crop's ecosystem were reviewed (Abd-Elgawad 2016a, c; Abd-Elgawad 2017a; Abd-Elgawad and Askary 2018). Such information is especially timely since most of these products are easily obtained with relatively cheap prices compared to chemical nematicides in Egypt (Table 1). On the other hand,

Table 1 Key commercial bionematicides and synthetic nematicides, their practical rates, and prices in Egypt*

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

* The host range assumed by the producers on the product labels is not necessarily confirmed in neutral tests (Wilson and Jackson 2013)

⁺ The rates are evenly applied to the soil (except oxamyl for foliar application too). In some cases, these rates may be incorporated into potting mix, field soil, or applied in greenhouses for which other doses are used (Abd-Elgawad 2020a)



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



Fig. 2 Root-knot nematodes (*Meloidogyne* spp.) inducing different gall sizes of eggplant roots

applying the entomopathogenic nematodes and their symbiotic bacteria or their byproducts to control different groups of pests in IPM programs has been suggested (Abd-Elgawad 2017a, b). For examples, these nematodes could effectively control both *M. incognita* on eggplant (Abd-Elgawad and Mohamed 2006) and *Tylenchulus semipenetrans* on Mandarin (Hammam et al. 2016) in Egypt. Additionally, agricultural extension should disseminate the best BCA use (Dougoud et al. 2018) via their interaction with the above-mentioned compatible inputs such as chemicals and organic manure. Such disseminations should also include accurate evaluation of efficient biocontrol programs (Abd-Elgawad 2016c), synergistic combinations against plant-parasitic nematodes (Abd-Elgawad and Askary 2018), developing techniques of BCAs against PPNs (Abd-Elgawad and Askary 2020), and registration of new BCAs against PPNs (Wilson and Jackson 2013; Hammam et al. 2016). Therefore, the expertise of research institutions in Egypt and elsewhere were brought together in the above-mentioned section to offer a realistic biocontrol of PPNs on eggplant. It provides a first approximation of the combined factors that could possibly contribute in such IPM programs.

Conclusions

Eggplant is a popular food crop in Egypt but many PPNs particularly RKNs and *Rotylenchulus reniformis* can significantly reduce its crop yield. Chemical nematicides

are effectively used to combat the nematodes but their irrational use may contaminate the environment and issue health problems. The effects of nematicides were reported and pesticides' residue studies have been informative (Abd-Elgawad 2008; Meena et al. 2020). Therefore, good agricultural practices and other preventive methods should be utilized in addition to BCAs as safe alternatives to control the nematodes on eggplant in Egypt. Numerous examples of such BCAs proved a promising tool in this direction. However, the complicated interactions among physical and biotic factors closely associated with such BCAs to optimize their benefits via safe and wise usage and upgraded technology should be well understood. Thus, accurate estimate of efficient biocontrol programs, synergistic or additive combinations including BCAs against PPNs, and effective techniques of harnessing novel and currently available BCAs against PPNs on eggplants should be carefully examined before utilization.

Abbreviations

PPN: Plant-parasitic nematode; BCAs: Biological control agents; IPM: Integrated pest management; Pi: Nematode-initial population; Pf: Nematode-final population; Rf: Nematode-reproduction factor.

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Authors' contributions

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