

REVIEW ARTICLE

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# Biological control agents in the integrated nematode management of potato in Egypt

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## Abstract

**Background:** Potato represents Egypt's largest vegetable export crop. Many plant-parasitic nematodes (PPNs) are globally inflicting damage to potato plants. In Egypt, their economic significance considerably varies according to PPN distribution, population levels, and pathogenicity.

**Main body:** This review article highlights the biology, ecology, and economic value of the PPN control viewpoint. The integration of biological control agents (BCAs), as sound and safe potato production practice, with other phytosanitary measures to manage PPNs is presented for sustainable agriculture. A few cases of BCA integration with such other options as synergistic/additive PPN management measures to upgrade crop yields are reviewed. Yet, various attributes of BCAs should better be grasped so that they can fit in at the emerging and/or existing integrated management strategies of potato pests.

**Conclusion:** A few inexpensive biocontrol products, for PPNs control on potato, versus their corresponding costly chemical nematicides are gathered and listed for consideration. Hence, raising awareness of farmers for making these biologicals familiar and easy to use will promote their wider application while offering safe and increased potato yield.

**Keywords:** Biological control, Bionematicides, Integrated nematode management, Potato, Pesticide market

## Background

Potato, *Solanum tuberosum*, represents one of the most important root and tuber crops for food commodities. It globally ranks the fifth most important staple food crop (Orlando et al. 2020) with its most production in the temperate zones, followed by numerous subtropical and tropical countries (Devaux et al. 2014). Potatoes are used and marketed in different forms such as table potatoes, seed potatoes, potato tubers, processing potatoes, frozen potatoes, French-fried potatoes (French fries), and chips. In Egypt, based on imputation methodology of Food and Agriculture Organization (FAO), potato production in 2017 was about 4.33 million tons from harvested area of 163,939 ha (FAO 2020). Admittedly, in Egypt, the percentage of small-holder farmers, having less than 5 acres, is more than 80%. Thus, access of their owners to modern techniques and machinery is relatively difficult though potato production is considered

as good cash resources for them. Egyptian potatoes are locally consumed, processed, or exported abroad (Arab Gulf, Russia, European, and African countries). For exportation, potatoes are considered at the forefront of export vegetable crops with about 351 thousand tons of potato exported in 2017 (El-Anany et al. 2019). The most important factors affecting potato's production are certified seeds, favorable climate, adequate soil and cultivar, and good production practices in terms of appropriate time of planting, fertilization, irrigation, effective pest and disease management, and crop rotation. For the last one, it is better to plant potato of summer season after Egyptian clover (*Trifolium alexandrinum*) and to plant potato of winter season after maize (*Zea mays*). On the contrary, potato should not be planted after any solanaceous crops: carrot (*Daucus carota*) or sweet potato (*Ipomoea batatas*). Potatoes can be yearly cultivated for seven consecutive months from mid-August to mid-February in three following seasons in Egypt. The first is the summer season (planted in December to mid-February) representing about 35% of the annual potato area.

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Delaying cultivation of this summer season until late February and early March may lead to a shortage of crop yield. This yield reduction is probably due to the thermal stress on the plants during hot June and sunburn, as well as their increased invasion by insect pests and viral diseases. Therefore, contrary to early cultivation of potato in this season, it is advised not to use these late plantings as a source of potato seeds for the following two seasons. Typically, the seed for cultivating in the summer season is imported from Europe, and harvest takes place from early April to mid-July. Its yield is used for the local market (from May to the end of October), early export to Europe (April), or seeds of the following two seasons which are called as winter and late fall plantations. As for the winter or Nili season (from mid-August to the end of October), it occupies the largest area for annual production (55%), and the best date for planting is no later than mid-October, and its harvest begins from late October to mid-February. Its tubers are used for both the domestic market and export. Recently, a third season for potato cultivation represents about 10% of the annual production area and is grown between mid-October to mid-November. However, more attention should be given to this time of cultivation because potatoes may be subject to frost damage. So, it is advised to irrigate potato fields at close intervals and spray the plants with some compounds that contain amino acids and balanced fertilization (El-Anany et al. 2019). Furthermore, it is better to plant potato of this season at definite governorates with relatively mild weather such as El-Beheira, El-Ismailia, and El-Sharkia. Its potato yield is mostly used for exportation to Europe usually during the first months of the year (January–April).

Potato is subject to a plenty of various pests and diseases including plant-parasitic nematodes (PPNs) that diminish the quantity and quality of tuber yields, resulting in degraded economic value and marketability (Mugniéry and Phillips 2007). In this respect, contrary to chemical nematicides, biological control agents (BCAs) are emerging as safe tools to control PPNs in sustainable agriculture. Ibrahim (2006) compiled the PPN genera (and species) which are associated with growing potatoes as follows: the potato tuber rot nematode: *Ditylenchus* (*D. destructor*); the potato cyst nematode (PCN): *Globodera* (*G. rostochiensis*); the spiral nematode: *Helicotylenchus* (*H. dihystrera*); the root-knot nematodes (RKNs): *Meloidogyne* (*M. incognita*, *M. javanica*, and *M. hapla*); the root-lesion nematodes: *Pratylenchus* (*P. brachyurus*, *P. penetrans*, *P. coffeae*, *P. minyus*); and the reniform nematode: *Rotylenchulus* (*R. reniformis*). More recently, this compilation included *G. pallida*; *M. chitwoodi*; *M. fallax*; *M. arenaria*; *M. minor*; the false root-knot nematodes: *Nacobbus aberrans*; the cystoid nematode: *Thecavermiculatus andinus*; the stubby-root nematode: *Trichodorus* spp., *Paratrachodorus* spp.; and the yam nematode: *Scutellonema bradys* (Niere and Karuri 2018). Also, Orlando et al. (2020) recorded *Pratylenchus alleni*, *P.*

*crenatus*, *P. andinus*, *P. flakkensis*, *P. neglectus*, *P. scribneri*, and *P. thornei* in association with potatoes. Thus, it is apparent that numerous nematode species are recorded to inflict damage to potatoes, but few are considered globally. Gad et al. (2018) reported the presence of ten nematode genera, i.e., the root-knot nematode: *Meloidogyne*; the stunt nematode: *Tylenchorhynchus*, *Rotylenchulus*; the ring nematode: *Criconeimoides*; the dagger nematode: *Xiphinema*, *Helicotylenchus*; the cyst nematode: *Heterodera*; the needle nematode: *longidorus*; the root lesion nematode: *Pratylenchus*; and the pen nematode: *Tylenchus* as the most prevalent nematode genera in the surveyed potato fields of Egyptian counties. The loamy soils, followed by sandy loam, had the highest number of nematode genera with total occurrence of 166 and 126 times, respectively. *Meloidogyne*-second stage juveniles (J<sub>2</sub>s) showed the broadest distribution in the potato fields as it was found in four potato cultivars of the surveyed regions. Therefore, PPNs represent key barriers to enhance potato yield in size and quality in Egypt and elsewhere (Youssef 2013 and Niere and Karuri 2018). For example, Shaltout (2001) recorded 10% as potato yield losses due to the damage of plant parasitic nematodes in Egypt. Korayem et al. (2012) found a negative correlation between *M. arenaria* population densities and yield of potato cultivars Diamont and Désirée; this relation was non-significant. Nevertheless, they found that sugars were significantly decreased in the *M. arenaria*-infected tubers relative to the non-infected ones. The decrease was more in Désirée (13.3%) than in Diamont (10.3%) tubers. Eventually, it is quite acceptable that the conditions, which support proper growing of potato plants, are typically convenient for their relevant PPN survival and reproduction.

## PPNs of potato in Egypt

### Root-knot nematodes, *Meloidogyne* spp.

#### Importance and spread

These obligate parasites have a broad host range including potato roots and tubers in addition to many other plant species. So, root-knot nematodes (RKNs) are referred to as the most economically important group of parasitic nematodes. Moreover, several pathotypes or races may constitute a species. About 100 RKN species have been known (Karsen et al. 2013). However, a few species have been parasitizing potato. Contrary to other nematode genera, which have a survival stage like the cyst in the cyst nematodes, RKN populations are decreased rapidly in the absence of a suitable host due to the lack of such a stage. Those of the temperate zone includes *M. chitwoodi*, *M. hapla*, *M. fallax*, and *M. minor* (Wesemael et al. 2014). On the other hand, three species are considered important on potato in the tropics and subtropics including Egypt. These are *Meloidogyne incognita* as the most broadly distributed, followed by *M. javanica* and *M. arenaria* (Niere and Karuri 2018). Ibrahim et al. (2010) reported that *Meloidogyne* was the most

frequently sampled PPN genus associated with many host plants in Egypt. Also, Bakr et al. (2011) found that percentage of occurrence of *Meloidogyne* spp. was 96.26% in Egyptian fields of newly reclaimed areas, which are often planted with vegetable crops such as potato.

### Symptoms and damage

Symptoms of potato damage and RKN biology are generally similar to those reported on other crops in Egypt (Abd-Elgawad 2020). For example, potato plants suffer deficiency of nutrients and water (Fig. 1). Subsequently, stunting, premature wilting, leaf chlorosis, and delayed revival to sufficient irrigation are common (Grabau and Noling 2019). Nonetheless, both potato tubers and roots are infected and galled, but the first generation usually takes place primarily on the root system with different sizes and shapes of galls. The following RKN generations can penetrate the tubers (Pinkerton et al. 1991). When tubers are infected, warty or pimple-like swellings are found on the surface (Fig. 2). The penetration depth of tubers by RKNs differs presumably due to the tuber size and composition. The females are frequently found 1–2 mm below the skin. They feed on vascular tissue. All RKN species make necrotic spots which appear between the tuber surface and the vascular ring, a reaction to the laid eggs and the gelatinous matrix. As much as 12 generations were completed by *M. incognita* on susceptible potato plants under favorable environmental conditions; optimal soil temperature range is 21.1 to 26.7 °C in the potato rhizosphere (Santos 2001). This range is favorable for *M. incognita*, *M. javanica*, and *M. arenaria*; the three common species in Egypt (Ibrahim 1985). Plants showing such symptoms usually happen in aggregations or patches, but the time of their appearance differ according to the degree of cultivar susceptibility, nematode population level, and predominant environmental conditions. Extended distribution and

spread of RKNs occurs via infected tubers (seed potatoes); transplants of other susceptible plant species; mulching with infested soil; and movement of infested soil by field machinery, supplies, and watering (Abd-Elgawad and McSorley 2009).

### Disease complex

It may occur when RKNs interact with other pathogens. In Egypt, potato brown rot disease caused by the bacterium *Ralstonia solanacearum* is one of the most important diseases since many shipments of potatoes exported abroad were refused due to quarantine restrictions imposed on the potato brown rot (Kabeil et al. 2008). The most important interaction of RKNs on potatoes is possibly facilitating the route for this bacterium (Siddiqui et al. 2014). Additionally, the invasion of *M. incognita* to potatoes can break the plant resistance to bacterial wilt of potatoes (Jatala and Martin 1977). Niere and Karuri (2018) reported other RKN interactions with different fungi such as *Rhizoctonia solani* and *Verticillium* spp., which aggravate the inflicted damage by RKNs to quantitative and qualitative potato yield.

### The potato cyst nematodes (PCNs), *Globodera* spp.

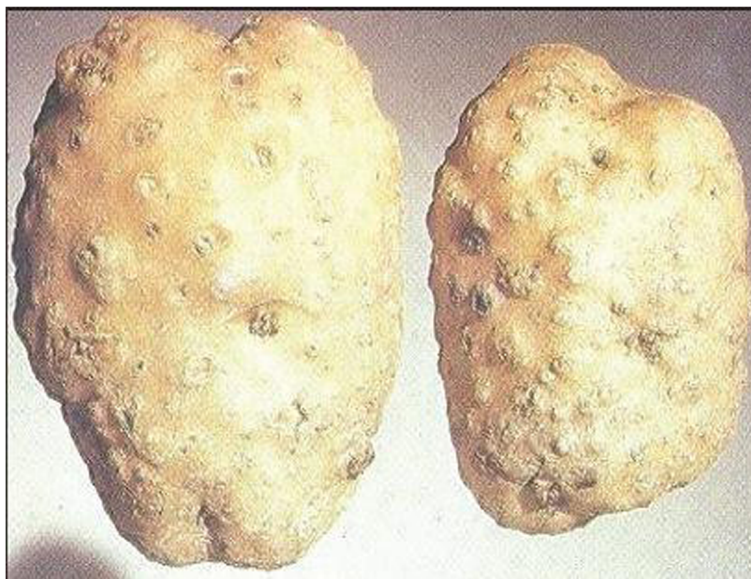
#### Importance and spread

Species related to *Globodera* are highly specialized parasites of plants. Contrary to RKNs, they have a quite narrow host range. However, their biology and life cycle resemble all cyst nematodes of their previously synonymized genus *Heterodera*. So, nematode eggs within the cysts can keep viable for numerous years. Because of their long-term strategy of survival within the cysts, serious damage to their host plants, and difficult control measures, PCNs are listed in quarantine regulations of more than 100 countries (Niery and Karuri 2018). *Globodera rostochiensis* and *G. pallida* are the most common PCN species, but other *Globodera*



**Fig. 1** Stunted potato plants with patchy distribution due to nematode infection on the right (especially on the second row of the orange mark) but vigorous plants treated with a nematicide on the left (Grabau and Noling 2019)





**Fig. 2** Visible nematode galls on two potato tubers induced by root-knot nematode (*Meloidogyne* spp.) in Egypt giving a warty tuber surface appearance

spp. of potato were recorded (Subbotin et al. 2010). For example, *Globodera ellingtonae*, *G. leptonepia*, and *G. capensis* need further studies of their pathogenicity and host range. Generally, PCNs are primarily distributed in temperate regions of the world but could be detected in warmer tropical and subtropical areas. Strikingly, *Globodera rostochiensis* was recently isolated from potato field, as a new record of the country, from El-Nobarria, El-Behera governorate in northern Egypt. It is the only species of this genus (Ibrahim et al. 2017). Being a serious parasite and a potential pest on potato and other solanaceous crops, further investigations are required concerning its distribution, damage, and economic importance as well as other cyst nematode species in Egypt. Schemes distinguishing PCN populations according to their virulence, races, and pathotypes have been in progress for their accurate characterization. Such differential schemes are usually based on host suitability designations, i.e., cultivars with susceptibility/resistance to PCNs. However, resistance-breaking pathotypes may take place. The frequent emergence of these pathotypes indicates the dire need to minimize selection pressure on PCN populations in the field via cultivating potato in relatively long rotations with adequate and other options for PCN control. Although the selection of new virulent phenotypes will still happen, the cultivation of resistant potato cultivars remains the most available ecofriendly and economically sustainable management measure on infested fields (Niere and Karuri 2018).

#### Symptoms and damage

As with other PPNs, symptoms associated with PCN infections result from root injury and consequent stresses of

reduced water and nutrient uptake (Fig. 1). Thus, the only method to determine the nematode genus/species infecting the potato plant is via isolation and identification of the infecting nematodes. Trudgill and Cotes (1983) reported early plant senescence as frequently associated with PCN infection. Also, tuber weight decrease usually happens (Schomaker and Been 2013). The distribution of PCN infestation foci in fields may often lead to dispersed patches of infected plants. It is apparent that these symptoms are not specific to PCN infestations but such patchy distribution (Fig. 1) of generally PPN-infected plants is quite common (Abd-Elgawad and Hasabo 1995). Admittedly, the magnitude of plant damage is highly impacted by the PCN population density in the soil, potato cultivar-tolerance or resistance level, agricultural practices, and environmental conditions. The PCNs, like other PPNs, often spread passively due to their very limited movement in soil. This passive spread can be via potato crop residues, PCN-contaminated machinery, soil mulching, especially to modify soil texture in newly reclaimed areas, infested-potato seeds, irrigation water, and field supplies (e.g., contaminated bags, containers). Composting and heat treatment are effective against PCNs. Clean planting material along with clean equipment is the best way to prevent the introduction and spread of PPNs such as PCNs. Needless to remind that absence of nematode-specific symptoms can further embarrass early detection. Fields unknowingly infested may help nematode spread to uncontaminated fields/areas. Although PCNs are host specific, other plant species are involved in their limited host range. These may comprise eggplant, tomato, and a few solanaceous weeds. However, Evans and Stone (1977) reported that these plant species are not considered as efficient hosts.



### Disease complex

As other sedentary, endoparasitic nematodes, PCNs usually furnish entry sites for fungi and bacteria which aggravate potato yield losses via disease complexes (Storey and Evans 1987). Such interactions have been recorded between *Globodera pallida* and *Verticillium dahliae* (Franco and Bendezu 1985), *Ralstonia (Pseudomonas) solanacearum* (Jatala et al. 1976), and *Rhizoctonia solani* (Back et al. 2006). Although PCNs are considered the most important nematode pests of potato, yield losses are shaped by such factors as PCN species, virulence type, potato cultivar, and population density, as well as ecological and biological factors (Niere and Karuri 2018). Turner and Subbotin (2013) recorded 9% losses of potato yield due to PCNs. Moreover, such losses may end with total loss of the crop when PCNs are left uncontrolled. On the other hand, increased potato production costs in the presence of PCNs will be due to increased amounts of fertilizers, application of nematicides, and limitations on using PCN-infested area as phytosanitary measures. Hence, in large scale potato-production systems, economic consequences are likely to be higher than that of small scale systems.

### Other plant-parasitic nematodes of potato

It should be stressed that PPN genera/species of potential economic importance on potato cultivation usually differ from one country/region to another. Therefore, their economic importance as major parasites of potato may vary from one region to another. For example, those important in Florida, USA are *Meloidogyne* spp., *Belonolaimus longicaudatus*, and *Nanidorus minor* (Grabau and Noling 2019). Moreover, other PPNs such as *Nacobbus aberrans* and *Ditylenchus* spp. have been studied in details on potato in a few countries except Egypt. In Egypt, such nematode species were mostly found in association with other field crops. In this respect, few species of the genus *Ditylenchus* were common on certain host plants including potato, i.e., *Allium cepa*, *Arachis hypogaea*, *Cynodon dactylon*, *Hordeum vulgare*, *Oryza sativa*, *Phoenix dactylifera*, *Plantago major*, *Solanum tuberosum*, *Thymelaea hirsuta*, *Vicia faba*, and *Zea mays* with 21.7% frequency of occurrence (Ibrahim et al. 2010). To the best of my knowledge, *Nacobbus* sp. was detected only from a tomato field (Oteifa 1960) hitherto. Nevertheless, PPN species such as those related to nematode genera *Pratylenchus*, *Tylenchorhynchus*, *Longidorus*, *Rotylenchulus*, *Xiphinema*, and *Hoplolaimus* are scattered mostly with variable population densities and much less frequencies of occurrence than RKNs in various cropping systems of Egypt, especially in light, followed by silty soils. Therefore, their suspected pathogenicity and threshold levels deserve more studies especially on potato plants. Action thresholds for managing RKNs are as low as they equal just one individual of any RKN species per 100 cm<sup>3</sup> of potato-cultivated soil as

pre-plant population density (Abd-Elgawad and Askary 2015). As in Florida, USA, the latter authors reported these thresholds to be 1, 80, 1, 40, and 10 individuals of the nematode genera *Belonolaimus*, *Pratylenchus*, *Trichodorus*, *Tylenchorhynchus*, and *Dolichodorus* (the awl nematodes), respectively per 100 cm<sup>3</sup> of soil prepared for potato cultivation. Damage thresholds of the cyst nematodes for tuber yield may differ according to edaphic and biotic factors and environmental conditions (CABI 2020). On the other hand, host suitability designations of many potato cultivars against both *Meloidogyne javanica* and *R. reniformis* were recently reviewed and appraised (Montasser et al. 2019). Also, *Pratylenchus* spp. were so abundant in an Egyptian field located at Giza governorate that their nematicidal control could increase potato cv. Spunta yield production by 30% relative to the untreated check (Mohammed and Elkelany 2017). Globally, Orlando et al. (2020) stressed that certain lesion nematode species like *P. neglectus*, *P. penetrans*, and *P. scribneri* can degrade quantitative and qualitative tuber yield of potato. In contrast, in newly reclaimed area in North West Egypt, the most predominant nematode genera were *Meloidogyne*, *Tylenchorhynchus*, *Helicotylenchus*, and *Rotylenchulus reniformis*; they had both the highest population levels and percentage frequency of occurrence (Korayem et al. 2015). Generally, one or more of these PPN species may be found in some potato fields at both high frequencies of occurrence and population levels. So, such species require further studies at least to investigate their economic significance, and consequently, action thresholds may be defined.

### Pre-considerations for managing PPNs on potato

Basically, the scenario of cultivating potato should be carefully and rightly examined. It should include perfect phytosanitary measures and the correct choice of potato cultivar that fits both the targeted market for the tubers and its reaction to the present PPN species/levels. Farmers should use a reasonably profitable and management option(s). These may involve utilizing nematicides and/or cultural practices, e.g., cover crops, resistant cultivars, crop rotation, biofumigation, and biological control. Grasping the limitations of the available crop protection strategies is important (Orlando et al. 2020). These options may comprise combination of compatible and preferably additive/synergistic control measures and other agricultural inputs such as fertilizers and organic amendments. Growers should assure the absence of any surviving PPN in plant residues and/or susceptible species of any weeds and volunteer plants. Moreover, the existing pests and pathogens, other than PPNs, should be taken into account to predict potato yield losses in terms of relating productivity to all yield-forming and yield-reducing factors such as edaphic factors, seed quality, irrigation management, harmful/beneficial organisms

in the field, and fertilization materials and techniques. Also, PPN damage should be carefully assessed because nematodes may directly damage potato yield or indirectly predispose potato plants to infection by other pests and pathogens which increase crop losses. Even transmitting virus diseases can take part in causing more yield reductions (Grabau and Noling 2019). Such notorious organisms may be found in soil and/or potato seeds as well. Therefore, certified seeds and soil/root sampling rank high as pre-considerations.

#### Certified potato seeds

In Egypt, insufficient quantities of certified potato seeds represent a major problem to improve potato productivity and quality. Growers usually depend on importation of such seeds from European countries via hard currency which adversely affect their profits. Such an importation occurs for cultivating potato of the summer season (El-Anany et al. 2019). The Egyptian Ministry of Agriculture is vigorously trying to enhance quality of local seed potato via an integrated package of activities and instructions. This includes applying the regulations and rules of The Centre Administration for Seed Testing and Certification and effective phytosanitary measures. It implements an internal potato quarantine program which delimits pest free areas, i.e., areas in which *R. solanacearum* has not detected yet with an end in view to eradicate the brown rot disease (Kabeil et al. 2008 and El-Anany et al. 2019). Additionally, private sector in Egypt has been contributing to provide certified potato seeds through definite terms in a series of processes to produce certified seeds in Egypt (Hegazy 2020). Clearly, it is time to urge both governmental and private sides to produce sufficient quantities of certified potato seeds. Abd-Elgawad (2020) stressed that the stakeholders in Egypt should face this issue collectively in order to appropriate funds necessary to get our national certified seeds/seedlings of economically important plant species. Specifically, the use of clean and healthy planting material is the best approach to block the spread of *Nacobbus aberrans* (Nieme and Karuri 2018). Generally, seeds of certifiable potato materials should be free from all notorious organisms such as bacteria, nematodes, fungi, and other transmissible pathogens (Abd-Elgawad et al. 2016).

#### Pre-plant sampling

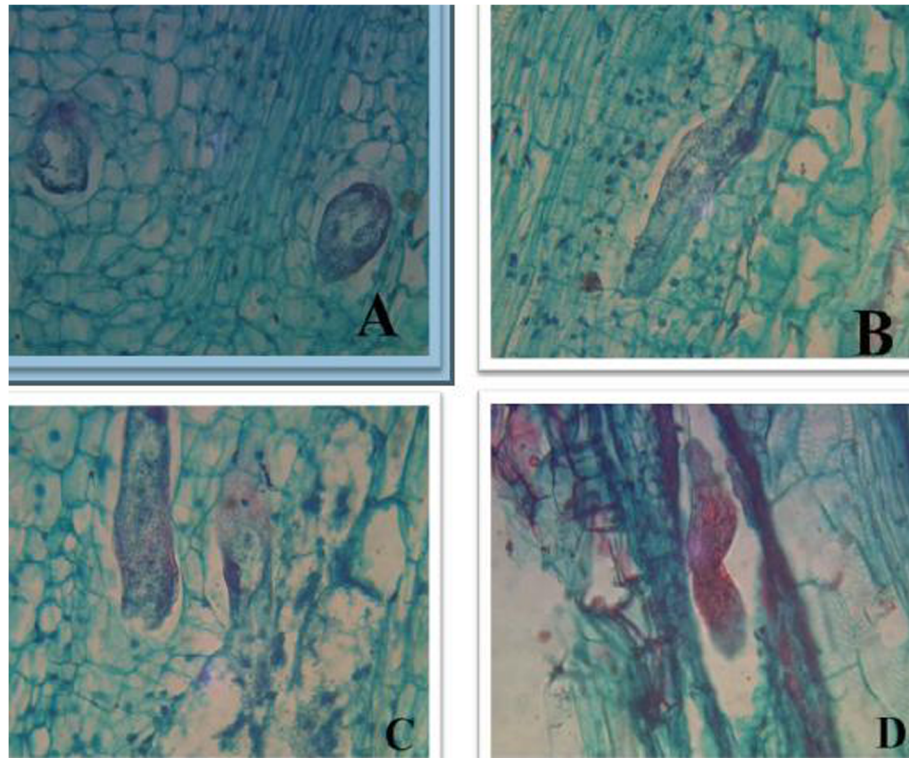
As sampling of nematodes is basic to nematode research and investigation, it must start well before sowing for the best PPN management and should continue during the crop cycle if necessary. Pre-plant nematode population density ( $P_i$ ) is usually related to yield loss as a predictor, especially in relation to establishing an advisory service for farmers and also for determining PPN population dynamics and how  $P_i$  relates to final nematode population density ( $P_f$ ) over a season's growth of potato. This offers important

information when establishing the damage potential of a pest and how population dynamics relate to the accrued damage caused by the nematodes. Nematode sampling may be utilized in an advising capacity to impose management measures that can suppress PPN populations to non-damaging densities, or in research to examine the reactions of PPN populations to such measures and other human-related activities, or to grasp relations between population levels and biological/ecological factors. Sampling may also determine the spatial pattern of PPN population levels in the sampled potato field. Such information would allow farmers to choose the best potato cultivar suited for specific locations based on previously known host-suitability designations (e.g., Montasser et al. 2019) or to foster variable rate approaches for nematicidal applications at levels that can manage local PPN populations to the required levels. Moreover, improving optimum size of nematode samples via iteration was established, and ranges for selecting sampling accuracy was presented to help in case of limited fund (Abd-Elgawad 2016).

### General tactics for managing potato nematodes in Egypt

#### Crop resistance and rotation

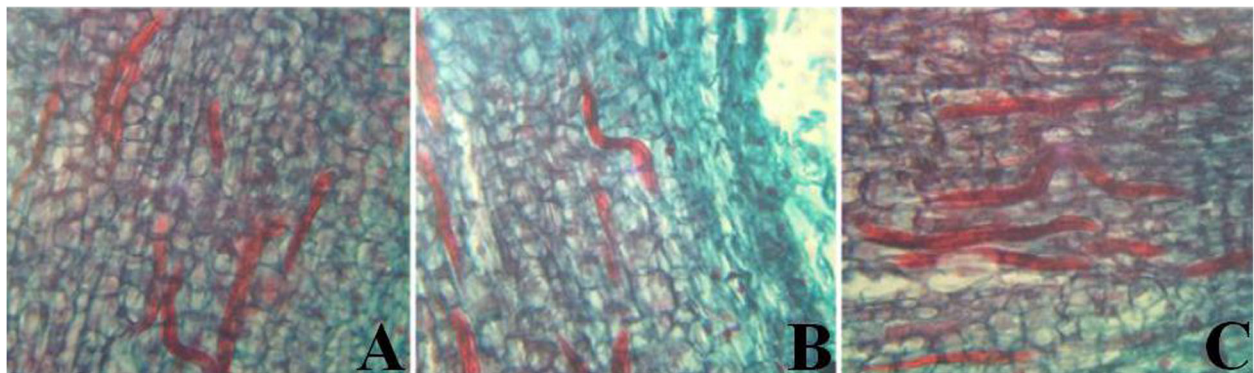
Certain potato cultivars are resistant to the most damaging and common species of PPNs (Youssef 2013; Nieme and Karuri 2018 and Montasser et al. 2019). Therefore, crop rotation with resistant plant cultivars/species or/and non-host crops is advised especially against the two most economically important PPN groups, PCNs and RKNs. For example, potato genotypes with resistance to *M. incognita* (Abd-Elgawad et al. 2012) and *M. chitwoodi* have been identified (Teklu et al. 2016). While nematodes can penetrate and develop on potato plants susceptible to *M. incognita* (Fig. 3), they may penetrate but cannot develop on resistant ones (Fig. 4). Also, both polygenic and monogenic genes for resistance to potato cyst nematodes have been identified, and markers closely linked to these alleles have since been developed for use in potato-resistance breeding programs (Fosu-Nyarko and Jones 2015). However, for effective crop sequence against these PPN groups, all susceptible hosts comprising volunteer potatoes should be absent. Sikora (1984) suggested a number of rotations for the PCN control where multiple cropping of potato was possible. Long period rotations of 6–8 years in Europe are quite sufficient to manage PCNs, but such long rotations are always not convenient with most Egyptian farmers of small land holding. Such majority of growers prefer to practice intensive production systems. Therefore, alternative control measures to long rotations should be sought. In this respect, Montasser et al. (2019) investigated resistance/susceptibility of potato cultivars, commonly grown in Egypt, against *M. javanica* and *R. reniformis* infection. They found that the cultivar Kuras was highly



**Fig. 3** Light micrograph of susceptible potato tetraploid clone O2T.157.16 reaction to juveniles of *Meloidogyne incognita* penetration. **a**, **b**, and **c** are 6 days after nematode inoculation. **a** Two different recently formed giant cells. **b** Immature nematode female. **c** A giant cell is formed around one of two developing nematode females. **d**. Ten days after nematode inoculation (Abd-Elgawad et al. 2012)

resistant to *M. javanica* whereas the cultivars Lady Rosetta, Belleni, Solana, Bresius, Hermes, and Synergy were highly resistant to *R. reniformis*. Likewise, cultivars with resistance to PCNs can reduce their field populations by 60–90% (Van Riel and Mulder 1998). Potato cyst nematode can hatch and attack the roots of resistant potato cultivars but cannot complete its life cycle in the resistant plants. Pathotype schemes for the classification of potato cultivars resistant to PCNs are utilized as yet, but they are

regarded as imperfect (Niere and Karuri 2018). That is because the virulence of the existing PCN population should be determined as a pre-requisite to select resistant potato cultivar(s). Further developing of molecular methods for rapid virulence determination can help solve this issue and replace the current time-consuming bioassay required for such determination. Moreover, the extracted nematode cysts may not perform all the spectrum of virulence established in the sampled field. Furthermore,



**Fig. 4** Light micrograph of resistant potato tetraploid clone O2T-155.6 reaction to juveniles of *Meloidogyne incognita* penetration; 10 days after nematode inoculation. **a**, **b**, and **c** show many invasions of nematodes but with dead or no nematode development (Abd-Elgawad et al. 2012)



rapid selective pressure on the population usually results from using resistant cultivars. Therefore, a management approach aimed at delaying such a pressure on virulent populations is needed to prolong the resistance (Fournet et al. 2016). Eventually, novel sources of potato resistance to PCNs can supposedly enable the use of relatively short crop rotation periods in the future. Likewise, control measures similar to that applied for the PCNs may also be fostered to manage other PPN genera/species as long as the relevant resistant cultivar(s) and/or non-host plant species are used.

### Chemical nematicides

Fumigant and non-fumigant chemical nematicides will decrease early nematode infection, consequently upgrade potato yields concerning the above-mentioned PPN genera/species in most conditions. Nevertheless, such nematicides may not stop yield losses and nematode reproduction especially when PCNs have high initial population levels. Whether PPN population densities can reach the same pre-plant densities after nematicidal application, or in some conditions even raise population size after harvest ( $P_f$ ), will rely on the mode of action and extent of biodegradation of the nematicide (Trudgill et al. 2003). Factually, synthetic chemical nematicides have been commonly used in PPN management practices in Egypt. The Egyptian Ministry of Agriculture advised several nematicides as oxamyl (commercial name Vaydate 24% SL) and ethoprophos (commercial name Nimayuk 10% GR) at rates of 3 l/Feddan (= 4200 m<sup>2</sup>) and 30 kg/Feddan, respectively against RKNs. Oxamyl is applied twice, at planting and 3–4 weeks thereafter, but ethoprophos is used once at seeding. Its recommendation (Anonymous 2018) is extended to include control of *Pratylenchus* spp. on potato using ethoprophos (commercial names Mocap 10% GR or Nimayuk 10% GR) and fosthiazate (commercial name Nemathorin 10% GR). Ethoprophos and fosthiazate are used at rates of 30 kg/Feddan and 12.5 kg/Feddan, respectively at planting time. New active chemicals for managing PCNs are currently under investigation (Norshie et al. 2016) but consumer concerns and ecological pollutions are urging growers to look more closely at safe alternatives. Admittedly, chemical nematicides are still a key management measure especially in developing countries like Egypt.

### Joining together the practical knowledge on biocontrol of PPNs on potato

#### The prioritized choice

Applied and fundamental research that can offer insights into the progress of PPN management on potato using biological control tactics and strategies are gathered hereafter. However, it should be stressed that in all conditions when one or more economically important PPN species are detected, an integrated nematode management (INM) program is the prioritized choice. Such a program should

be designed to provide the most economically feasible method(s) of reducing/keeping PPN population levels beneath the damage threshold, to prevent dissemination of nematodes, and block or at least delay the development of virulent populations.

### Examples of BCAs

Using the fungus *Purpureocillium lilacinum* against *Meloidogyne incognita* and *Globodera pallida* on potatoes has been successfully tried (Jatala et al. 1979, 1980). Also, *Pseudomonas fluorescens* Migula (Pi) formulated in talc at  $15 \times 10^8$  colony-forming units/gram was applied at two rates 10 and 20 kg per ha, and carbofuran at 1 kg a.i./ha could lessen *Globodera* spp. on potato roots by 47.7, 62.6, and 81.3%, respectively (Mani et al. 1998). In parallel, tuber production was enhanced by 29.4, 39.4, and 77.8%, respectively. However, they observed that PCNs were in the J<sub>4</sub> or adult stage in case of *P. lilacinum* but were in the J<sub>2</sub> or J<sub>3</sub> under carbofuran. When different species of *Pseudomonas* were singly applied as BCAs in pot experiment, the bacterial strains *P. aurantiacea* 13 (2) and *Pseudomonas putida* 3 (2) could decrease population densities of *Globodera rostochiensis* by 40.7–42.2% relative to the untreated check with consequent increase in plant growth parameters (Trifonova et al. 2014). Mohammed and Elkelany (2017) assessed a few commercial bio-products for managing *Pratylenchus* spp. infecting potato cv. Spunta and yield increase under field conditions. These bio-products could suppress the nematode population levels and enhance tuber yield. The best tuber production had 30% more weight relative to the untreated control. It was achieved by the bionematicides Stanes Sting which contained the bacterium *Bacillus subtilis* in combination with the biofertilizers Microbien, Phosphorine and Potassiumag. Niere and Karuri (2018) reviewed other options, e.g., the bacterium *Rhizobium etli*, that have potential control against the potato nematodes under controlled conditions. Castillo et al. (2017) found a correlation between *P. neglectus*, *M. chitwoodi*, and rhizosphere bacteria, present in five potato farms (USA) where the farms with the fewest PPNs had greatest densities of *Arthrobacter* spp., *Bacillus* spp., and *Lysobacter* spp. So, they proposed that some bacteria may possess a significant role in controlling these PPNs in potato soils. In this vein, definite “parasitic” fungi such as *Hirsutella rhossiliensis*, *Verticillium balanoides*, and *Drechmeria coniospora* and trapping fungi such as *Arthrobotrys oligospora*, *Monacrosporium ellipsosporum*, and *Nematoclonus* spp. which produce adhesive conidia have also been examined for potential biocontrol of *P. penetrans* on potato, but just *H. rhossiliensis* has proven effectiveness (Orlando et al. 2020). The exact scope of such options requires further assessment and optimization of biocontrol potential. For example, trap crops that induce PCN-egg hatching and block the multiplication of

the nematodes are significant component in management programs. Hence, certain cultivars of oca (*Oxalis tuberosa*) and barley are useful in preventing such hatching (Franco et al. 1999). These cultivars have been tested abroad, therefore, caution should be exercised when introducing plant species/cultivars non-native to any Egyptian region. Moreover, Dutta et al. (2019) reviewed PPN management via biofumigation, using brassica and non-brassica plants. Biofumigation crops especially *Brassica juncea* liberates glucosinolates that had nematicidal effect on PCNs after mixing into the soil.

#### Differential host reaction

It is hypothesized that the biocontrol efficacy of a definite BCA may vary from one host plant species to another. Bourne et al. (1996) found that *Pochonia chlamydosporia* was more effective in parasitizing *Meloidogyne incognita* eggs on potato than on tomato. That is probably because more eggs are exposed on the small galls of potato roots than embedded eggs within large gall tissues of the tomato roots. So, these latter are relatively kept from *P. chlamydosporia* parasitism. Moreover, applying *P. chlamydosporia* together with inducers of plant defense (benzothiadiazole) was recommended as a control strategy against RKNs on potato (Vieira dos Santos et al. 2014). Conversely, colonization by BCA may vary among plant species. The fungus *P. lilacinum* was more plentiful in the rhizosphere of some plants such as sugar beet and oilseed rape than in others such as potato rhizosphere in the absence of nematodes (Manzanilla-Lopez et al. 2011). Also, biocontrol of PCNs has been accomplished using *P. chlamydosporia* under field conditions in the UK (Tobin et al. 2008). Likewise, the arbuscular mycorrhizal fungi have been reported as BCAs against PCNs (Deliopoulos et al. 2008).

#### Future prospects of biocontrol approaches for PPNs on potato in Egypt

##### The need to expand BCA usage

Orlando et al. (2020) concluded that the application of BCAs for PPN control on potatoes has potential, but it is not well developed, and its utilization in agriculture is generally restricted. Hence, researchers and stakeholders should make wise and full use of the above-mentioned reports of gains in managing PPNs on potato via fostering ecofriendly control measures. Basics to such a trend are to consider biological and ecological factors in the targeted area for potato cultivation. These may comprise the history of the crop/field, PPN species, other fauna and flora present and their levels, and edaphic factors as important principles in choosing management strategies for a specific potato field. On the other level, growers need to consider safe alternative methods to hazardous nematicides. Egyptian farmers, like many others especially in developing countries, have been used to evaluate control based on

quick knockdown caused by the nematicides. However, BCAs often work more slowly, less effectively, and require more sophisticated criteria for measuring their efficacy (Abd-Elgawad and Askary 2020). Therefore, such a type of mindset shift is necessary for encouraging wider utilization of bionematicides.

#### Priority considerations

Close attention should be paid to the BCA applications considering the above-mentioned factors and mechanisms affecting the PPN population densities to optimize the biocontrol tactics especially focusing on integrated pest management in Egypt (Abd-Elgawad and Askary 2020). Firstly, proper time, process, and method of PPN sampling are essential to detect and diagnose nematode issues (Abd-Elgawad 2020) in the context of the above-mentioned sampling objectives. Secondly, functional sampling to improve isolation frequencies of BCAs should be utilized. The latter author used a new type called functional sampling to extract, characterize, and deploy relatively large numbers of biological strain(s) with possibly differential pathogenicity against insect and nematode pests. Moreover, understanding the exact interactions between BCAs and biotic/abiotic factors which are in close contact with them on potato in the field should be exerted to perfect the targeted management of PPNs. To boost biocontrol of PPNs on potato, BCA application should fit into existing or emerging INM tactics and strategies. Therefore, improving novel (compatible) application approaches or leveraging additive/synergistic effects that involve BCAs should be sought (Abd-Elgawad 2020). For instance, plant dry weight of the shoot system had significantly more gain, when *P. fluorescens* was integrated with organic manure for controlling *M. incognita* than applying either organic manure or *P. fluorescens* alone (Siddiqui et al. 2001). Furthermore, INM may not only apply different categories of compatible PPN control measures but also can utilize different components of BCAs in addition to favorable chemical nematicide. For instance, number and weight of potato tubers/plant had better ( $P \leq 0.05$ ) increase, when *Pochonia chlamydosporia*, *Pseudomonas fluorescens*, and *Trichoderma viride* were combined with the nematicide carbofuran than using either of these BCAs or carbofuran alone. Such an increase was accompanied by significant reduction in the PCN populations of eggs and juveniles (Muthulakshmi et al. 2012). On the other hand, filamentous *Trichoderma*, mycorrhizal, and endophytic fungi are inducers of resistance against nematodes. They can decrease the damage caused by PPNs directly via antibiosis, parasitism, paralysis and by the production of lytic enzymes. They enable plant to tolerate PPN infection by supplying higher nutrient and water uptake to the root system, by space and resource-competition, or by modifying the root morphology, and/or rhizosphere interactions, that forms a merit for the plant-

growth. Also, filamentous fungi can induce resistance against PPNs by activating hormone-mediated (e.g., salicylic and jasmonic acid, strigolactones) plant-defense mechanisms. In this respect, *Trichoderma harzianum* could constitute hyphal colonization in the rhizoplane and the rhizosphere of the potato, possibly providing long-term protection to the PPN infection (Poveda et al. 2020).

### Indigenous BCAs

Although global products of BCAs are accessible, Abd-Elgawad (2020) advocated the importance of using indigenous biologicals. These latter (Table 1) are less expensive, more adapted, and without any risk to Egyptian environment which should encourage their wider utilization. The relatively high efficacy proved via applying indigenous but various BCAs (Abd-Elgawad and Kabeil 2012) on different crops clearly indicates the priority to develop them into registered, ready-for-sale protection products against PPNs on potato too. They can replace or at least take part with chemical nematicides. Clearly, promoting their effectiveness should be sought in earnest. For example, fostering the *T. harzianum* efficacy was possible via its integration with organic amendments, e.g., wheat bran-peat preparations or oil cakes (Abd-Elgawad and Kabeil 2012). Thus, Abd-Elgawad (2020) revised the various classes of BCAs to distinguish current processes that can affect their application for nematode control and alternatives for their optimization against PPNs. Moreover, various approaches were speculated to decrease expenses, ease accessibility, improve application, and increase efficacy of such BCAs. In this respect, to lessen costs, the BCA producer/company can simultaneously act not only as the distributor but also as a certified applicator to oversee and follow-up the use of BCAs. Certified applicators and agricultural extensions should be well-trained to solve bionematicide-related issues such as the viability of BCAs, contamination, and BCA fate/persistence. A company with such different aspects of responsibilities can have cost-effective processes

of BCAs while offering sound follow-up of the PPN control programs. These tactics and the likes should be considered especially because other BCA-containing products are being in the production pipeline or will be available soon. Therefore, nematologists and researchers, backed by stakeholders, must identify and address research priorities for harnessing bio-nematicides in sustainable agriculture via grasping the biology, ecology, and interactions with other cultural inputs. Such topics were recently addressed by Abd-Elgawad and Askary (2020) who also reported mechanisms of action for many BCAs and related information. The latter comprised the active ingredient, product name and formulation type, producer, targeted nematode species and crops, and country of origin for global nematicidal products. Moreover, pitfalls and issues affecting favorable outcomes of biocontrol programs against PPNs were discussed (Abd-Elgawad and Askary 2020).

Labels of the BCA products usually instruct growers for adequate storage and application procedures. They may also offer other immediate rate-modifying suggestions. Nevertheless, dissemination of updated progress in BCAs technology should be transferred to growers and agricultural extensions to raise their awareness and guidance for using these biologicals. Thus, boosting the interest in the strategies of biological control can make BCA products familiar and easy to use. If so, growers will unlikely pay a premium to use chemicals when there are low-cost alternatives as those biologicals (Table 1). In other words, farmers' perceived need to manage PPNs, the expense of BCAs compared with other nematode control options, the price of the potato tubers (e.g., per ha), and its overall significance in the market are economic factors that should be considered since they guide growers in selecting the appropriate control measure. Additionally, to lessen the negative influence on the environment, it is fairly acceptable that chemicals can take part to some extent with bionematicides. The only formal bionematicide reported by the Egyptian Ministry

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

| Active ingredient  | Product name  | Application rate (product/feddan <sup>-1</sup> ) <sup>a</sup> | Price per acre |
|--|---------------|---|----------------|
| 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      |
| 10 <sup>9</sup> CFU/ml of <i>Serratia</i> sp., <i>Pseudomonas</i> sp., <i>Azotobacter</i> sp., <i>Bacillus circulans</i> , and <i>B. thuringiensis</i> | Micronema     | 30 l/feddan (thrice)/year                                     | L.E. 600       |
| 10 <sup>8</sup> units/ml <i>Purpureocillium lilacinus</i>  | Bio-Nematon   | 2 l/feddan/ year  | L.E. 500       |
| 10 <sup>9</sup> bacterium cells of <i>Serratia marcescens</i> /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-oxoethanimidodithioate)  | Vydate 24% SL | 4 l/feddan (twice)/year                                       | L.E. 2800      |

One US dollar = 16 L.E. There are broad host range claims by the manufacturer's product labels which have not necessarily been confirmed in independent trials

<sup>a</sup>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



of Agriculture to control potato nematodes is abamectin; its commercial product, Tervigo 2% SC, is recommended at the rate of 2.5 l/feddan. Abamectin is generated by *Streptomyces avermitilis*. The active ingredient of the utilized product is abamectin (20 g/l). It possesses unique chelated formulation which secures perfect guard of the active ingredient for immediate contact with nematodes and offers favorable soil penetration. Abamectin contains 80% and 20% of avermectin B1a and B1b, respectively. This active ingredient can impede the transmission of electrical activity in invertebrate, like PPNs, nerve, and muscle cells. Such mechanism of action is done mostly by promoting the effects of glutamate at the invertebrate-specific glutamate-gated chloride channel with minor effects on gamma aminobutyric acid receptors. Flow of chloride ions into these tissues/cells is induced, causing hyperpolarization and paralysis of PPN neuromuscular systems. The product is quite effective against many PPN genera. It has several advantages as a soluble concentrate form that can act primarily by contacting PPNs (Abd-Elgawad 2020).

## Conclusions

Potatoes are considered the first exporting vegetable crop in Egypt. So, increasing potato production should be achieved to boost the incoming hard currency. An important approach to fulfill this increase is to control potato pests. Plant-parasitic nematodes rank high among these pests. This article presented the most important methods to manage nematode pests affecting potato yields but it focused on biologicals as safe alternatives to hazardous chemical nematicides. The implementation of biocontrol for PPN management on potatoes has potential, but it is not well sophisticated. In order to expand its usefulness, given the remarkable role of BCAs in sustainable agriculture, integrated pest management should be practiced as a fundamental approach to optimize their safe and profitable use. Various BCAs that could suppress the nematodes and increase potato production are reported herein to draw attention to their gains in sustainable agriculture in Egypt. Their use should be optimized. For instance, integration of BCAs with other compatible agricultural inputs such as soil amendments and compatible nematicides for leveraging additive/synergistic effects against the nematodes is preferable. Therefore, researchers and stakeholders must identify and address research priorities for harnessing bio-nematicides for upgrading potato production. This duty necessitates better understanding of these BCAs in terms of their ecology, biology, interactions with other cultural inputs, and modes of action. Also, enhancing awareness of growers and agricultural extensions is essential for making these biologicals familiar and easy to use which will pave the way for their broader application.

## Abbreviations

BCAs: Biological control agents; P<sub>i</sub>: Initial nematode population density; P<sub>f</sub>: Final nematode population density; PCN: Potato cyst nematode; RKNs: Root-knot nematodes; INM: Integrated nematode management; IPM: Integrated pest management; PPN: Plant-parasitic nematode; J<sub>2</sub>: Second-stage juvenile

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## Author's contributions

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

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## 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

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The author declares that he has no competing interests.

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## References

- Abd-Elgawad MMM (2016) Biological control agents of plant-parasitic nematodes: a review. *Egypt J Biol Pest Cont* 26(2):423–429
- Abd-Elgawad MMM (2020) Optimizing biological control agents for controlling nematodes of tomato in Egypt. *Egypt J Biol Pest Cont* 30:58 <https://doi.org/10.1186/s41938-020-00252-x>
- Abd-Elgawad MMM, Askary TH (2015) Impact of phytoneematodes on agriculture economy. In: Askary TH, Martinelli PRP (eds) *Biocontrol agents of phytoneematodes*. CAB International, Wallingford, pp 3–49
- Abd-Elgawad MMM, Askary TH (2020) Factors affecting success of biological agents used in controlling plant-parasitic nematodes. *Egypt J Biol Pest Cont* 30:17 <https://doi.org/10.1186/s41938-020-00215-2>
- Abd-Elgawad MMM, Hasabo SA (1995) Spatial distribution of the phytoneematode community in Egyptian berseem clover fields. *Fundam Appl Nematol* 18: 329–334
- Abd-Elgawad MMM, Kabeil SSA (2012) Biological control of *Meloidogyne incognita* by *Trichoderma harzianum* and *Serratia marcescens* and their related enzymatic changes in tomato roots. *Afr J Biotech* 11:16247–16252
- Abd-Elgawad MMM, McSorley R (2009) Movement of citrus nematode-infested material onto virgin land: detection, current status and solutions with cost-benefit analysis for Egypt. *Egypt J Agronematol* 7(1):35–48
- Back M, Haydock P, Jenkinson P (2006) Interactions between the potato cyst nematode *Globodera rostochiensis* and diseases caused by *Rhizoctonia solani* AG3 in potatoes under field conditions. *Eur J Pl Pathol* 114:215–223
- Bakr RA, Mahdy ME, Mousa EM (2011) A survey of root-knot and citrus nematodes in some new reclaimed lands in Egypt. *Pak J Nematol* 29(2):165–170
- Bourne JM, Kerry BR, de Leij F (1996) The importance of the host plant on the interaction between root-knot nematodes (*Meloidogyne* spp.) and the nematophagous fungus, *Verticillium chlamydosporium* Goddard. *Biocont Sci Tech* 6:539–548
- CABI (2020) *Globodera rostochiensis* (yellow potato cyst nematode). <https://www.cabi.org/isc/datasheet/27034>. Accessed 24 June 2020

- Castillo JD, Vivanco JM, Manter DK (2017) Bacterial microbiome and nematode occurrence in different potato agricultural soils. *Microb Ecol* 74:888–900
- Delipoulos T, Haydock PPJ, Jones PW (2008) Interaction between arbuscular mycorrhizal fungi and the nematicide aldicarb on hatch and development of the potato cyst nematode, *Globodera pallida*, and yield of potatoes. *Nematology* 10:783–799
- Devaux A, Kromann P, Ortiz O (2014) Potatoes for sustainable global food security. *Potato Res* 57:185–199
- Dutta TK, Khan MR, Phani V (2019) Plant-parasitic nematode management via biofumigation using brassica and non-brassica plants: current status and future prospects. *Curr Pl Biol* 17:17–32
- El-Anany AM, Abdel-Aziz F, Khafagy, EY (2019) Potato cultivation and production. Technical issue No. 1376 (In Arabic), Central Administration of Agricultural Extension, Ministry of Agriculture, Egypt.
- Evans K, Stone AR (1977) A review of the distribution and biology of the potato cyst nematodes *Globodera rostochiensis* and *G. pallida*. *Proc Natl Acad Sci U S A* 23:178–189
- FAO (2020) Potato pro. Com, Egypt. <https://www.potatopro.com/egypt/potato-statistics>. Accessed 19 June 2020
- Fosu-Nyarko J, Jones MGK (2015) Application of biotechnology for nematode control in crop plants. *Advan Botanic Res* 73:339–376
- Fournet S, Eoche-Bosy D, Renault L, Hamelin FM, Montarry J (2016) Adaptation to resistant hosts increases fitness on susceptible hosts in the plant parasitic nematode *Globodera pallida*. *Ecol Evol* 6:2559–2568
- Franco J, Bendezu E (1985) Estudio del complejo *Verticillium dahliae* Kleb. Y *Globodera pallida* Stone y su efecto en el comportamiento de algunos cultivares peruanos de papa. *Fitopatologia* 20:21–27
- Franco J, Main G, Oros R (1999) Trap crops as a component for the integrated management of *Globodera* spp. (potato cyst nematodes) in Bolivia. *Nematropica* 29:53–62
- Gad SB, El-Sherif AG, Osman MA (2018) Survey of plant-parasitic nematode genera associated with potato plants at Dakahlia governorate, Egypt. *J Plant Pathol Microbiol* 9:3. <https://doi.org/10.4172/2157-7471.1000436>
- Grabau ZJ, Noling JW (2019) Nematode management in potatoes (Irish or White). University of Florida publication Series no. ENY-029, USA, p 12
- Hegazy S (2020) Seed potato production in Egypt. [https://www.unece.org/fileadmin/DAM/trade/agr/meetings/ge.06/2009/Egypt\\_PPTs/S4\\_SalahHegazy.pdf](https://www.unece.org/fileadmin/DAM/trade/agr/meetings/ge.06/2009/Egypt_PPTs/S4_SalahHegazy.pdf). Accessed 24 June 2020
- Ibrahim IKA (1985) The status of root-knot nematodes in the Middle East, region VII of the international *Meloidogyne* project. In: Sasser JN, Carter CC (eds) *Advanced treatise on Meloidogyne*, Vol I, biology and control. North Carolina State Univ. Graphics, Raleigh, pp 373–378
- Ibrahim IKA (2006) Diseases and pests of vegetable crops and control methods. Monshaat Al-Maarf Publisher, Alexandria, Egypt
- Ibrahim IKA, Handoo ZA, Basyony ABA (2017) The cyst nematodes *Heterodera* and *Globodera* species in Egypt. *Pak J Nematol* 35(2):151–154
- Ibrahim IKA, Mokbel AA, Handoo ZA (2010) Current status of phytoparasitic nematodes and their host plants in Egypt. *Nematropica* 40:239–262
- Jatala P, Gutarra L, French ER, Arango J (1976) Interaction of *Heterodera pallida* and *Pseudomonas solanacearum* on potatoes. *J Nematol* 8:289–290
- Jatala P, Kaltenbach R, Bocangel M (1979) Biological control of *Meloidogyne incognita acrita* and *Globodera pallida* on potatoes. *J Nematol* 11:303
- Jatala P, Kaltenbach R, Bocangel M, Devaux AJ, Campos R (1980) Field application of *Paecilomyces lilacinus* for controlling *Meloidogyne incognita* on potatoes. *J Nematol* 12:226–227
- Jatala P, Martin C (1977) Interaction of *Meloidogyne incognita acrita* and *Pseudomonas solanacearum* on *Solanum chacoense* and *S. sparsipilum*. *Proc Amer Phytopathol Soc* 4:178
- Kabeil SS, Lashin SM, El-Saadani MA, Abd-Elgawad MM, Aboul-Einean AM (2008) Potato brown rot disease in Egypt: current status and prospects. *Am Eurasian J Agric Environ Sci* 4(1):44–54
- Karssen G, Wesemael W, Moens M (2013) Root knot nematodes. In: Perry RN, Moens M (eds) *Plant nematology*, 2nd edn. CAB International, Wallingford, UK, pp 73–108
- Korayem AM, Mohamed MMM, Abou-Hussein SD (2012) Damage threshold of root-knot nematode *Meloidogyne arenaria* to potatoes grown in naturally and artificially infected fields and its effect on some tubers properties. *J Appl Sci Res* 8(3):1445–1452
- Manzanilla-Lopez RH, Esteves I, Powers SJ, Kerry BR (2011) Effects of crop plants on abundance of *Pochonia chlamydosporia* and other fungal parasites of root-knot and potato cyst nematodes. *Ann Appl Biol* 159:118–129
- Mohammed HHA, Elkelany USF (2017) Control of root lesion nematode *Pratylenchus* spp. infesting potato cv. Spunta under field conditions through biotic products. *Egypt Acad J Biol Sci* 9(3):197–202
- Montasser SA, Anany AE, Khalifa AE (2019) Screening of some potato cultivars for root-knot nematode (*Meloidogyne javanica*) and reniform nematode (*Rotylenchulus reniformis*) infection under greenhouse conditions. *Egypt J Agronematol* 18(1):60–69
- Mugniéry D, Phillips MS (2007) The nematode parasites of potato. In: Vreugdenhil D (ed) *Potato biology and biotechnology: advances and perspectives*. Elsevier Science, Amsterdam, pp 569–594
- Muthulakshmi M, Kumar S, Subramanian S, Anita B (2012) Compatibility of *Pochonia chlamydosporia* with other biocontrol agents and carbendazim. *J Biopesticides* 5:243–245
- Niere B, Karuri HW (2018) Nematode parasites of potato and sweet potato. In: Sikora RA, Coyne D, Hallmann J, Timper P (eds) *Plant parasitic nematodes in subtropical and tropical agriculture*. CAB International, Boston, USA, pp 222–251
- Norshie PM, Grove IG, Back MA (2016) Field evaluation of the nematicide fluensulfone for control of the potato cyst nematode *Globodera pallida*. *Pest Manag Sci* 72:2001–2007
- Orlando V, Grove IG, Edwards SG, Prior T, Roberts D, Neilson R, Back M (2020) Root-lesion nematodes of potato: current status of diagnostics, pathogenicity and management. *Pl Pathol* 69:405–417 [doi.org/10.1111/ppa.13144](https://doi.org/10.1111/ppa.13144)
- Oteifa BA (1960) A synoptic key to common nematodes associated with crop plants in Egypt. *Bull Fac Agric, Cairo Univ* 20:73–9
- Pinkerton JN, Santo GS, Mojtahedi H (1991) Population dynamics of *Meloidogyne chitwoodi* on russet Burbank potatoes in relation to degree-day accumulation. *J Nematol* 23:283–290
- Poveda J, Abril-Urías P, Escobar C (2020) Biological control of plant-parasitic nematodes by filamentous fungi inducers of resistance: *Trichoderma*, mycorrhizal and endophytic fungi. *Front Microbiol* 11:992. <https://doi.org/10.3389/fmicb.2020.00992>
- Santos GS (2001) Root knot nematodes. In: Stevenson WR, Loria R, Franc GD, Weingartner DP (eds) *Compendium of potato diseases*, 2nd edn. APS Press, St Paul, Minnesota, pp 51–53
- Schomaker CH, Been TH (2013) Plant growth and population dynamics. In: Perry RN, Moens M (eds) *Plant nematology*, 2nd edn. CAB Int, Wallingford, UK, pp 301–330
- Shaloot A (2001) Economic loss resulting from nematode-infected vegetables and fruits. *Proceedings of a workshop (In Arabic)*, Menoufia Univ, Egypt. Disease problems caused by nematodes in horticultural farms in Egypt, 43–50.
- Siddiqui ZA, Shehzad M, Alam S (2014) Interactions of *Ralstonia solanacearum* and *Pectobacterium carotovorum* with *Meloidogyne incognita* on potato. *Arch Phytopathol Pl Prot* 47:449–455
- Sikora RA (1984) Importance of diapause, resistant and early maturing potato cultivars, chicken manure and non-host crops for *Globodera rostochiensis* integrated control in the upland tropics. *Meded Fac Landbouw Gent* 49:613–620
- Storey GW, Evans K (1987) Interactions between *Globodera pallida* juveniles *Verticillium dahlia* and three potato cultivars, with descriptions of associated histopathologies. *Pl Pathol* 36:192–200
- Subbotin SA, Mundo-Ocampo M, Baldwin JG (2010) Systematics of cyst nematodes (Nematoda: Heteroderinae). In: Hunt DJ, Perry RN. (Series eds) *Nematology monographs and perspectives*, Volume 8A. Brill, Leiden, the Netherlands
- Teklu MG, Schomaker CH, Been TH, Molendijk LPG (2016) A routine test for the relative susceptibility of potato genotypes with resistance to *Meloidogyne chitwoodi*. *Nematology* 18:1079–1094
- Tobin JD, Haydock PPJ, Hare MC, Woods SR, Crump DH (2008) Effect of the fungus *Pochonia chlamydosporia* and fosthiazate on the multiplication rate of potato cyst nematodes (*Globodera pallida* and *G. rostochiensis*) in potato crops grown under UK field conditions. *Biol Control* 46:194–201
- Trudgill DL, Cotes LM (1983) Differences in the tolerance of potato cultivars to potato cyst nematodes (*Globodera rostochiensis* and *G. pallida*) in field trials with and without nematicides. *Ann Appl Biol* 102:373–384
- Trudgill DL, Elliott MJ, Evans K, Phillips MS (2003) The white potato cyst nematode (*Globodera pallida*) – a critical analysis of the threat in Britain. *Ann Appl Biol* 143:73–80
- Turner SJ, Subbotin SA (2013) Cyst nematodes. In: Perry RN, Moens M (eds) *Plant nematology*, 2nd edn. CAB Int, Wallingford, UK, pp 109–143
- Van Riel H, Mulder A (1998) Potato cyst nematodes (*Globodera* species) in Western Europe. In: Marks TJ, Brodie BB (eds) *Potato cyst nematodes: biology, distribution and control*. CAB Int, Wallingford, UK, pp 274–298

- Vieira Dos Santos MC, Curtis RHC, Abrantes I (2014) The combined use of *Pochonia chlamydosporia* and plant defence activators – a potential sustainable control strategy for *Meloidogyne chitwoodi*. *Phytopathol Medit* 53: 66–74
- Wesemael WML, Moens M, Viaene N, Taning LM (2014) Life cycle and damage of the root-knot nematode *Meloidogyne minor* on potato, *Solanum tuberosum*. *Nematology* 16:185–192
- Youssef MMA (2013) Potato nematodes and their control measures: a review. *Arch Phytopathol Pl Prot* 46(11):1371–1375

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