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REVIEW ARTICLE

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Entomopathogenic nematodes as potential and effective biocontrol agents against cutworms, *Agrotis* spp.: present and future scenario

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Abstract

Background: Cutworms (*Agrotis* spp.) are cosmopolitan and polyphagous pests distributed throughout world, which belong to the family Noctuidae, and about 26 species are found associated with agriculturally important crops in India and some other countries of world. The most prominent species belonging to genera *Agrotis* are *Agrotis ipsilon*, *A. flammatra*, *A. plecta*, *A. spinifera* and *A. segetum*. Cutworms cause substantial damage to many agricultural and horticultural crops particularly, at the seedling stage. This pest produces vitiating symptoms with a young stage (larvae) by feeding on the epidermis of leaves and eating away parts of the stem, tubers, etc.

Results: This review article is mainly focused on management of cutworm, which is very challenging due to larval hiding behaviour during the day time and feed actively at night. Efficient chemical control of cutworm may be obtained by adequately applying chemicals when young caterpillars are still on the leaves and therefore vulnerable. As per biology of cutworms, these pests remain hidden in cracks and crevices during most of life cycle so chemical control is often ineffective and economic. Sometimes, inadequate application of these chemicals is resulted into the development of resistance in these pests. Moreover, the adverse effects of the chemicals have led researchers to search for new control strategies. Recently, biological control has become a practical option for eco-friendly management of numerous insect pests. Among biological control, entomopathogenic nematodes (EPNs) have broad potential to kill the cutworms in soil itself.

Conclusions: Various species of EPNs like *Steinernema* spp. and *Heterorhabditis* spp. are found a quite effective and hold considerable potential to manage cutworms. So, the use of EPNs for the management of cutworms is a good alternate to chemical method.

Keywords: *Agrotis* spp., Biological control, Entomopathogenic nematodes, *Heterorhabditis* spp., *Steinernema* spp

Background

Insect pests are significant constraints of many agricultural, horticultural and forest crops worldwide. Cutworms are important polyphagous pests belonging to order Lepidoptera and family Noctuidae (Sharma 2016). Several species of cutworms, viz. *Agrotis* spp., *Peridroma saucia*, *Spodoptera frugiperda*, *S. exigua and S. littoralis*, are responsible for causing severe damage to most of the economic plants. Most of the agriculturally important cutworms belong to genera *Agrotis*, and among them, the most damaging species of this genera are like: *A. spinifera*, *A. ipsilon*, *A. flammatra*, *A. plecta*, *A. longidentifera* and *A. segetum* are reported in India (Napiorkowska and Gawowska 2004). These group of insects cause extensive damage by cutting seedlings at colour regions and eating

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only the tender parts of plants. Larvae of cutworms usually feed at night, hiding in cracks and crevices in the soil or under clumps/litter piled around the plants during the day. During night-time feeding, they cut down the stem of their host plants, causing severe damage and rapid crop loss, especially at the seedling stage (Angulo et al. 2008). The caterpillars emerging from the eggs grow by passing through several molts until they attain full size and pupate in the ground, and moths emerge from these pupae. The complete life cycle of cutworm may take a month to a year, depending on the type of species and weather conditions prevailing. Due to their cosmopolitan distribution, cutworms are found in various climatic and nutritional conditions. Crop losses by these pests are more severe due to their hidden lifestyle during day time, feeding behaviour, prolonged egg laying and ability to migrate long distance (Capinera 2001). More than 80 percent of the loss occurred after reaching the 4th instar of larvae, which cuts several plants, most preferably at the initial stages of seedlings during night. Various chemicals are found ineffective against *A. ipsilon* larvae due to the development of resistance against these pesticides and their hiding behaviour during daylight hours (Takeda 2008). Furthermore, the negative impact of chemical pesticides on the environment and human health has prompted researchers to seek new control strategies (Laznik and Trdan 2012) like cultural, physical, biological control, etc. Among biological control, various bio-agents like fungi (*Trichoderma* spp., *Paecilomyces lilacinus*, etc.), bacteria (*Bacillus* spp., *Pseudomonas fluorescens*, etc.), viruses, mites and entomopathogenic nematodes (EPNs) are pretty effective in pest management strategies.

EPNs are effective and emerging alternative for managing this insect, and these can be utilized in classical, conservation and augmentative biological control programs. Generally, EPNs are identified from 23 nematode families but the two most important families of EPNs are Steinernematidae and Heterorhabditidae (Koppenhöfer and Kaya 2001). The infective juveniles (IJs) of genera *Steinernema* and *Heterorhabditis* are associated with their symbiotic bacteria, *Xenorhabdus* spp. and *Photorhabdus* spp., respectively, which cause septicemia leading to the death of the insects within 24–48 h. EPNs are easy to apply and effective against most lepidopterans (Shapiro-Ilan et al. 2002). These nematodes have a good host searching ability, high virulence, ease of culturing and safety to non-target organism have led to successful integration into pest management programs to control of soil-borne pests, especially cutworms (Hussaini 2014). Many species of EPNs can recycle plant nutrients persisting in the environment. They may have direct or indirect effects on populations of plant parasitic nematodes (PPNs) and plant pathogens, which help in improving soil quality in one or other possible ways. These are compatible with a wide range of chemicals, viz. insecticides, fungicides, herbicides, fertilizers and biological pesticides used in integrated pest management (IPM) programs (Lacey and Georgis 2012).

In this review, some selected literature on the flourishing and efficiently use of EPNs for eco-friendly management of cutworms (*Agrotis* spp.) were incited. Distribution, host range, nature of the damage, economic importance, seasonal dynamics and management methods of cutworms with the effective use of EPNs were enumerate.

Distribution and host range of cutworms

Cutworms as uncertain origin are distributed in many regions of the world but found absent from some tropical regions and cold areas. These cutworms are more damaging in northern hemisphere. In Europe, China, and North America, long-distance dispersal of adults has long been suspected. In the spring, the general trend is to travel north and in the autumn to go south. In the USA, studies have shown that when moths are aided by northward-blowing wind, they can travel up to 1000 km north in 2–4 days during the spring. In the autumn, similar movement to the south and southwest was seen (Story and Keaster 1982).

In India, almost 26 species of cutworms (*Agrotis* spp.) are well known yet. However, *A. ipsilon* and *A. segetum* are the most common and damaging species under genera *Agrotis* distributed in most of the parts of India (Chandel and Chandla 2003). Cutworms are cosmopolitan and polyphagous pests that feed on a wide range of field and vegetable crops. Generally, *A. ipsilon* was reported from most of potato-growing regions of India mainly concentrating on the belt from Punjab to Bengal and Madhya Pradesh in Central India (Lal and Rohilla 2007). This species is also reported dominantly and highly abundant in cole crops from the region of Srinagar, J&K (Bhat 2018). In the cold desert of Ladakh, nearly all vegetables are known to be attacked by *A. ipsilon* (Pandey et al. 2006). Vegetable crops like cabbage, cauliflower and knol-khol are frequently attacked by *A. ipsilon* and *A. flammatra* in north-eastern belt of India (Sachan and Gangwar 1990). Other economically crucial crops attacked by cutworms include cotton, barley, oats, tobacco, lucerne, wheat, mustard, groundnut, sunflower, maize, sorghum, lentil, linseed, sugarcane, gram, sorghum, bajra, cowpea and berseem (Pal and Katiyar 2010). *A. ipsilon* favours the host plants full of sugar and protein contents compared to cultivars having high phenolic and chlorophyll content (Nath and Nag 1996). Some other damaging species of *Agrotis* recorded from parts of India are *A. spinifera* causing damage to potato crop in

Karnataka (Singh 1989) and *A. nigrosigna* Moore, (1881), causing damage on *Mentha arvensis* in J&K (Kriti et al. 2014). Generally, weeds serve as an alternate host for developing cutworms during the off-crop season, including *Chenopodium album*, *Solanum nigrum*, *Portulaca oleracea*, *Amaranthus viridis* and *Evolvulus alsinoides* (Das and Ram 1988). Adults of cutworms feed on nectar from flowers of the host crop, and moths are particularly attractive to the deciduous trees where they lay eggs.

Nature of damage and economic importance of cutworms

Moths of cutworm are generally attracted to the green vegetation to lay eggs and feed on young tender crop parts or weeds. The late instar larvae may snip the stems of seedlings immediately below the ground surface, causing them to wilt and die. They may cut the stems thoroughly, leading to a significant reduction in stands. Usually, the insects feed at night or on overcast days. Sometimes the larvae drag the cut plants under soil clods or into small holes in the soil to continue their feeding during the daytime. Larvae cut plants just above or close to the soil surface. Most of the plant remains intact, but adequate tissues are generally removed from the stem to cause it to fall over. The larvae feed above ground plant parts by leaving small irregular-shaped holes in the leaves. (Lal and Rohilla 2007). Once the fourth instar stage is reached, these larvae can cause significant damage by cutting the young plants and one larva may damage several plants in a single night (Verma 2015). Early instar larvae of *A. ipsilon* feed on the leaves, whereas older instar stages feed at the base of stems in Kashmir (Kriti et al. 2014).

In India, *A. segetum* is a more serious pest on maize crop during the summer season than rainfed conditions and attacks at the seedling stage throughout the North-Western Himalayan regions (Sidhu 2019). In the Chamba district of Himachal Pradesh, 46.69 percent reduction in maize yield was recorded due to infestation of these cutworms (Thakur and Kumar 1999), whereas in the Kangra valley, mortality of maize seedlings has been reported to be 16.80 percent at the two-leaf stage (Viji 1998). *A. ipsilon* is an early-season pest of cotton, which is more severe, particularly in southern states. Laxman et al. (2014) reported that *A. ipsilon* could cause damage to both *Bacillus thuringiensis* transgenic (*Bt*) and non-*Bt* plants, but the level of infestation was slightly more in non-*Bt* cotton (8.78–12.62%) as compared to *Bt* cotton (6.39–9.19%). Pathania (2010) reported the attack of cutworms in vegetables, which caused more severe damage in tomato, potato, brinjal, beans, capsicum, cabbage, peas and cucurbits. Among cucurbits, cucumber is highly susceptible to this pest attack.

In some vegetable crops like brinjal, tomato and chilli, cutworms are routinely reported to move from one plant to another and feed on the below-ground portion of each seedling, which usually resulting into the death of the plants (Chandel et al. 2016). In endemic areas of North-Western Himalaya, the extent of damage of this pest has been reported in different vegetable crops such as tomato (30.71%), brinjal (35.41%), capsicum (65.73%), cabbage (29.41%), cauliflower (21.95%), French bean (40.64%), pea (31.05%), cucumber (32.65%) and bitter gourd (58.65%) (Kumar et al. 2007). In addition to cutting the tender parts of a plant, the cutworms also damage potato tubers and fleshy roots of carrot, turnip, leek and beetroot (Verma 2015). Five species of *Agrotis* have been reported in potato from India, viz. *A. ipsilon*, *A. segetum*, *A. flammatra*, *A. intracta* and *A. spinifera*, and among them, *A. segetum* and *A. ipsilon* are the key species of cutworms in hills and plains, respectively (Chandel et al. 2012). The damage done by cutworms to potato tubers leads to the attraction of secondary pathogens, which further cause additive damage to potatoes.

EPNs and their role as biocontrol agents of cutworms

The most commonly used and effective species of EPNs belong to the families Steinernematidae and Heterorhabditidae. These families are classified into genera *Steinernema* Travassos, 1927 and *Heterorhabditis* Pionar, 1975. Generally, both genera have similar life cycles, and the only difference between the life cycles of *Heterorhabditis* spp. and *Steinernema* spp. is occurred in the first generation. *Steinernema* species reproduce amphimictically, which requires males and females for successful reproduction, whereas *Heterorhabditis* species are hermaphroditic in the first generation and can reproduce in the absence of conspecifics. These nematodes were associated with symbiotic bacteria from genera *Xenorhabdus* and *Photorhabdus* (*Sterinernema* spp. and *Heterorhabditis* spp., respectively), lethal parasites to most of soil inhabiting stages of insect pests (Shapiro-Ilan et al. 2017). EPNs have a facultative or obligate parasitic association with their insect hosts. In insects, they cause symptoms like reduced fecundity, sterility, longevity, flight activity, retard development and other morphological, behavioural and physiological aberrations leading to rapid mortality of infected insects. EPNs are only insect parasitic nematodes holding an optimal balance of biological control because of their ability to kill hosts quickly within 1–4 days, depending on nematode and host species. However, both families belong to the same order but are not closely related. These families also have different reproductive strategies (Blaxter et al. 1998).

Many natural enemies are enlisted in the biological control of cutworms, including flies, wasp parasites, pathogenic organisms such as granulosis virus, fungi, bacteria, protozoa and predatory beetles, reducing cutworm numbers to a certain level. However, there is a little evidence of their relative importance. Nevertheless, none of them could reduce the cutworm population within a short period. Biological control by EPNs appears to be a long-lasting alternative to control this pest. These are the most efficient and effective biocontrol organisms for most lepidopterans and other insects that can kill insects within 24–48 h. of infection based on nematode density. An EPN, *Hexamermis arvalis* (Nematoda: Mermithidae), brings down up to 60 per cent of larvae in the central USA.

Distribution of EPNs

EPNs are distributed in almost all soils with limiting environmental conditions, host availability, soil temperature and moisture status. Around 100 valid species of *Steinernema* and 21 species of *Heterorhabditis* have been identified from different countries of the world (Bhat et al. 2020). The effects of environmental and biotic factors contribute a lot to the distribution of EPNs in soil because the survival and infectivity of these nematodes depend on the same factors. For example, juveniles of *S. feltiae* can be infective at a temperature range from 2–30 °C and *S. carpocapsae* juveniles become inactive at 10 °C, whereas some *Heterorhabditis* spp. can infect host insects from 7 to 35 °C (Georgis et al. 2006). Various species of EPNs are predominantly isolated from subterranean conditions, notably in white grubs and weevils of the family Scarabaeidae and Curculionidae, respectively. A survey reported that most of the isolated EPNs from 2 genera (*Steinernema*, 3.0% and *Heterorhabditis*, 4.5%) were found in loam soils at 26–33 °C with pH of 5.0–7.0 in Nakhon Sawan and Uthai Thani area, in Thailand (Vitta et al. 2015). A survey in Fiji Islands by Kour et al. (2020) also reports that coastline and dunes were the most *H. indica*-rich habitats (25%), followed by river banks (15.1%).

Species identified from abroad and India to date

Various workers have conducted many surveys from almost all parts of the world to isolate locally adapted EPN species. To date, 100 species of genus *Steinernema* and 16 species of genus *Heterorhabditis* have been identified, isolated and described in the literature as in Bhat et al. (2020) (Table 1).

Economic importance of EPNs

EPNs are devastating organisms to major insect pests but do not threaten non-target organisms and the environment (Georgis and Hague 1991). Unlike harmful chemicals and other micro-organisms (ex. *B. thuringiensis*), EPNs provide a high degree of safety and do not require any special applications. Most bio-products require days or weeks to kill, but EPNs give effective results within 24 to 48 h due to their associations with pathogenic symbiotic bacteria (Akhurst and Smith 2002). Nematodes are amenable to mass production within a limit of time, and while applied in the field, nematodes are found compatible with most of the standard agro-chemicals and other biopesticides.

Table 1 List of *Steinernema* and *Heterorhabditis* species recorded from different parts of India (Bhat et al. 2020)

Sr. no.	Species identified	References
Steinernematids		
1	*S. thermophilum*	Ganguly and Singh (2000)
2	*S. carpocapsae*	Hussaini et al. (2001)
3	*S. tami*	Hussaini et al. (2001)
4	*S. bicornutum*	Hussaini et al. (2001)
5	*S. siamkayai*	Ganguly et al. (2002)
6	*S. dharanai*	Kulkarni et al. (2012)
7	*S. glaseri*	Kadav and Lalramliana (2012)
8	*S. surkhetense*	Bhat et al. (2017)
9	*S. sangi*	Lalramnghaki et al. (2017)
10	*S. pakistanense*	Bhat et al. (2018)
11	*S. cholashanense*	Mhatre et al. (2017)
12	*S. hermaphroditum*	Bhat et al. (2019)
Heterorhabditis		
13	*H. indica*	Poinar Jr et al. (1992)
14	*H. baujardi*	Vanlalhlimpuia and Lalramnghaki (2018)
15	*H. bacteriophora*	Bhat et al. (2020)

Isolation of EPNs

The collected soil samples from the field are taken into the laboratory, and up to 1/3rd capacity, honey glass bottles were filled with this soil. Five-to-ten live wax moth larvae (*Galleria mellonella* L.) are added to different soil layers to capture the nematodes as the insect bait (Bedding and Akhurst 1975). These filled bottles with soil are placed upside down and incubated at room temperature (~25 °C). After 48 h of incubation, the bottles were checked daily for 2 weeks, and in-between, any dead larvae of wax moth found in the soil were collected in the separate bottles. Dead larvae are thoroughly rinsed with distilled water and transferred to white traps (White 1927). White traps are placed at room temperature (~25 °C) until the emergence of the IJs, and the newly emerging IJs are collected in sterile deionized water and stored in a tissue culture flask at 15 °C for morphological and molecular characterization and further use in the field to control cutworms.

Mode of action of EPNs against cutworms

EPNs use two main foraging strategies; ambushers or cruisers for searching their host, but these strategies are based on the type of species of nematodes. *S. carpocapsae* is an example of an ambusher-type foraging strategy with an energy-conserving approach. It remains in wait for attacking the moving larvae of cutworm (nictitating) in the soil's upper layer. While the other side, *S. glaseri* and *H. bacteriophora* are examples of cruiser type of foraging strategy, and these nematodes are highly active. These nematodes continuously move significant distances in soil using volatile cues and other methods to find their host (Grewal et al. 1994). Some other species, *S. feltiae* and *S. riobrave*, use an intermediate foraging strategy (*i.e.* combination of ambush and cruiser type) to find their host insect. After reaching cutworms, IJs actively enter through natural openings such as the mouth, spiracles and anus or the inter-segmental membrane (Fig. 1). Once get enters the host body, the nematodes release symbiotic bacteria that kill the host through bacterial septicemia (Fig. 2). EPNs are a nematode–bacterium complex, and in this complex, the bacterium requires nematode for protection from the external environment, penetration into the host's haemocoel and inhibition of the host's antibacterial proteins (Sajnaga and Kazimierczak 2020). The nematode is dependent upon the bacterium for quickly killing its insect hosts, creating a suitable environment for its development by producing antibiotics that suppress competing secondary micro-organisms and transforming the host tissues into a food source. After insect death, the cadaver becomes red if the insects are killed by Heterorhabditids or brown to tan coloured if Steinernematids kill it. The colour of the dead insect cadaver is indicative of the pigments produced by the mutualistic bacteria growing in the blood of host insects.

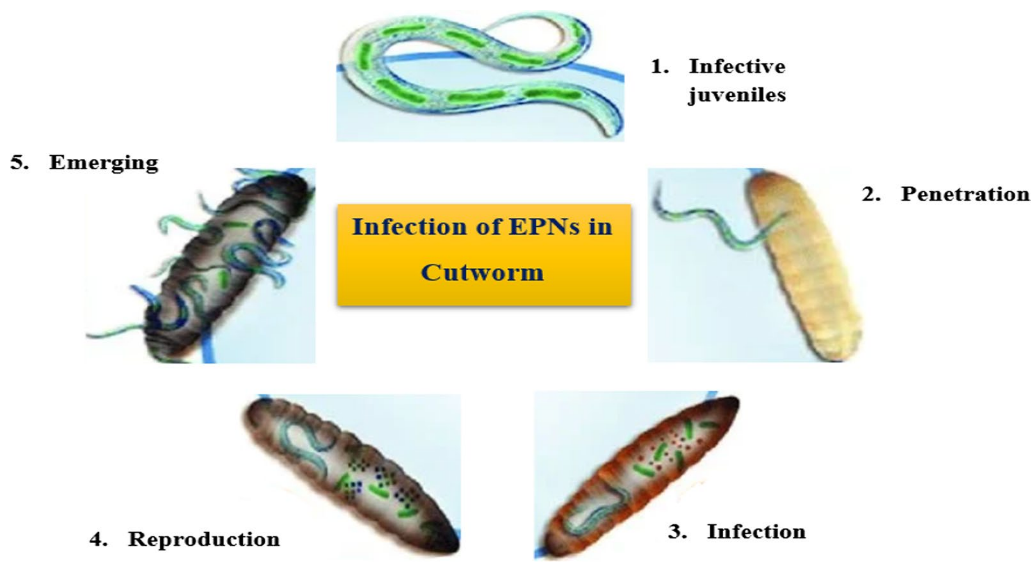

Fig. 1 Parasitic cycle of entomopathogenic nematodes in cutworm larvae

Fig. 2 Cutworm infected with entomopathogenic nematode, *Steinernema carpocapsae*

Symbiotic bacteria and their toxic substances

Entomopathogenic bacteria from the genera *Photorhabdus* and *Xenorhabdus* are closely related to Gram-negative bacilli from the family Enterobacteriaceae (γ-Proteobacteria). To facilitate insect pathogenesis, they have obligate mutualistic associations with soil nematodes from the genera *Steinernema* and *Heterorhabditis*. About 26 species of the genus *Xenorhabdus* and 19 species of the genus *Photorhabdus* have been identified so far (Sajnaga and Kazimierczak 2020). These bacteria take shelter in the midgut of infective juveniles of EPNs. EPNs are responsible for killing the targeted insects via direct infection by promoting the secondary metabolites and toxins produced by symbiotic bacteria inside the insect body. When the IJs of nematodes enter the mouth, anus or spiracles of insect hosts, symbiotic bacteria are released from their intestines into the haemocoel of target insects. Once bacteria gain entry into the host body, it starts replication rapidly and causes septicemia in insects. Several toxins secreted are known for their bioactive characteristics like cytotoxic, antimicrobial, antiparasitic and insecticidal (Fig. 3) (Junior da Silva et al. 2020).

The insecticide activity of *Xenorhabdus* and *Photorhabdus* species is related to protein production (Sheets et al. 2011) and secondary metabolites (Li et al. 1998). The secretion of high molecular weight toxins by *P. luminescens* and *X. nematophila* plays a vital role in insect mortality (Sheets et al. 2011). Similarly, *Xenorhabdus* produced toxins (Tcs) that induce immune suppression in insects by inhibiting eicosanoid synthesis (Park and Kim 2000). *X. nematophila* produces about eight suppressor metabolites of insect immunity (Eom et al. 2014).

Some species of *Photorhabdus* also produce a variety of toxins, including Tcs (toxin complexes), Mcf (make caterpillars foppy), Pvc (Photorhabdus virulence cassettes) and Pir (insect-related protein) (Rodou et al. 2010). The Tcs destroy epithelial cells from the middle intestine of insects, similar to δ-endotoxin of *B. thuringiensis* and acting on the actin cytoskeleton by the ADP-ribosyltransferases TccC3 and TccC5 in *P. luminescens* (Aktories et al. 2014). On the other hand, Mcf promotes hemocyte apoptosis in the haemocoel (Jallouli et al. 2010). It was also observed that *M. sexta* and *G. mellonella* are susceptible to Pvc. The *Photorhabdus* genus currently consists of *P. luminescens*, *P. temperata* and *P. asymbiotica*. The *P. luminescens* and *P. temperata* species recently split into subspecies due to DNA–DNA relatedness and 16S rDNA branching (Fischer-Le Saux et al. 1999). A total of 15 new species of genus *Xenorhabdus* were identified from Steinernematidae nematodes based on 16S rRNA gene sequencing, molecular typing and phenotypic characterization. These are viz., *X. budapestensis*, *X. ehlersii*, *X. innexi*, *X. szentirmaii*, *X. indica*, *X. cabanillasii*, *X. doucetiae*, *X. griffiniae*, *X. hominickii*, *X. koppenhoeferi*, *X. kozodoii*, *X. mauleonii*, *X. miraniensis*, *X. romanii* and *X. stockiae* (Tailliez et al. 2006). This increase in the number of described species is likely to grow as nematodes worldwide are collected and their symbiotic bacteria identified.

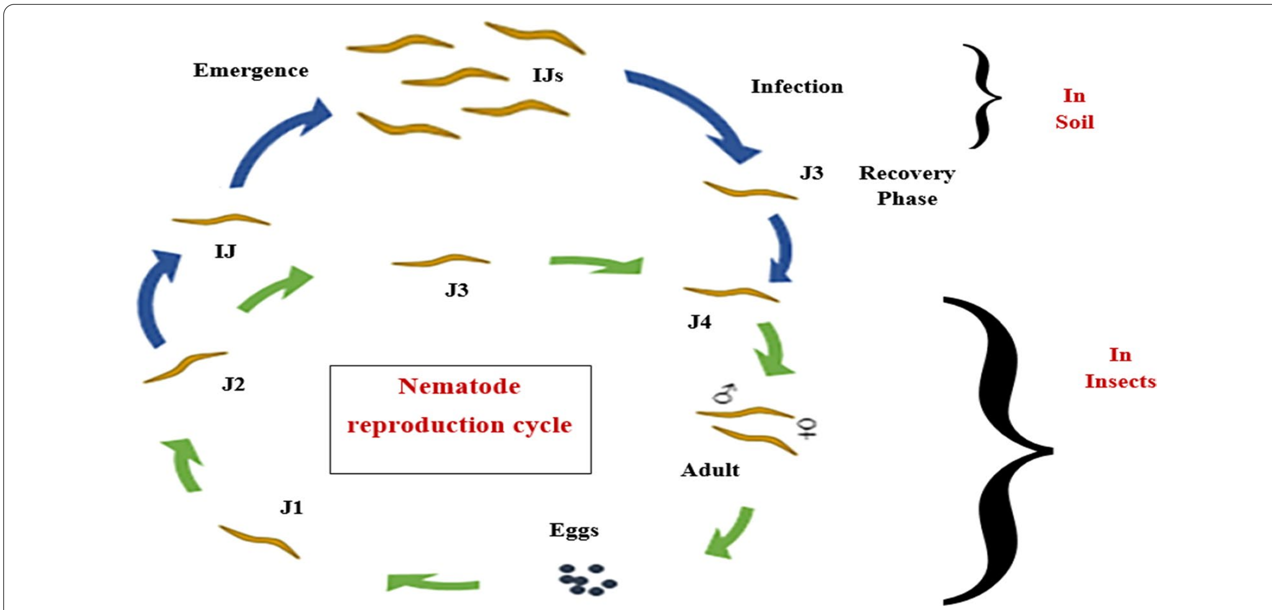

Fig. 3 Reproduction cycle of entomopathogenic nematodes (in soil—free living stages; in insects—parasitic stages)

Examples for successful biocontrol of cutworms by using EPNs

In vitro studies on the effect of *S. carpocapsae* Mex and *H. indica* LN2 against third instar larvae of *A. ipsilon* after 72 h resulted in 80.0 and 83.3% mortality. Trials in field conditions, both the species reduced the damage caused by *A. ipsilon* to the cabbage crop and increased the yield compared with chemical control (cyfluthrin) and *Bt*-bacteria (Han et al. 2014). Likewise, the application of *S. feltiae* in *A. segetum*-infested lettuce crop resulted in better yield when compared to endosulfan chemical treatment (Lossbroek and Theunissen 1985).

EPNs can provide excellent control of cutworms (*Agrotis* spp.) over most chemical pesticides in many different field crops. In a study, field application with *S. carpocapsae* reduced black cutworm (*A. ipsilon*) by 50% on maize (Capinera et al. 1988). Similarly, a single application of *S. carpocapsae* declined the number of cutworms in maize plants by 76–83% during the initial ten days of treatment (Levine and Oloumi-Sadeghi 1992). A single ground spray of *S. carpocapsae* at 1 billion IJs/ha or 2 applications of 0.5 billion IJs/ha caused 80 and 67% mortality of turnip moth (*A. segetum*) larvae, respectively, within 8-day interval (Yokomizo and Kashio 1996). In the greenhouse conditions, the lower application rate of *S. carpocapsae* is effective when applied at a dose of 12.5 IJs/cm^2 reduced the black cutworm, *A. ipsilon* (Hufnagel) damage in the field by more than 75%, which was higher than chemical insecticides (Levine and Oloumi-Sadeghi 1992). The efficacy of *S. abbasi* and *H. bacteriophora* has been evaluated under laboratory conditions against the late instar larvae of *A. ipsilon* and resulted in a 73% population reduction by *H. bacteriophora* at 100 IJs/larva after 48 h of infection (Shoeb et al. 2006).

The efficacy of *S. weiseri* (BEY), *S. feltiae* (TUR-S3) and *S. carpocapsae* (TUR) was tested against the last instar larva of *A. segetum* and found that *S. weiseri* was more virulent than *S. feltiae* (TUR-S3) at 50 and 100 IJs per larva (Unlu et al. 2007). Furthermore, 1000 IJs of *H. bacteriophora* per kg soil were enough to start the infection and reduce the late instar larval population of *A. segetum* up to 61.3% after 7 days of exposure (Chandel et al. 2009). The effectiveness of *S. carpocapsae* and *H. bacteriophora* against late instar *A. ipsilon* larvae at concentrations of 50 and 100 IJs/ml under laboratory conditions resulted in 85–100 mortality at 24 h (Fetoh et al. 2009). Similarly, *S. kraussei* at different population densities (100, 300 and 500 IJs) was also evaluated on *A. segetum* larvae at 25 °C and obtained the highest mortality of 98% 500 IJs within 7 days (Gokce et al. 2013). Some relevant studies on the effect of EPNs on capableness and efficient management of cutworms are listed below (Table 2).

Advantages of EPNs over other methods of cutworm control

- Warm-blooded vertebrates including human being remain unaffected by EPNs and their associated bacterial symbionts (Boemare et al. 1996), while for cold-blooded species, EPNs are harmful (Kermarrec et al. 1991).
- When compared to other biological agents, they take less time to kill the insects (24–48 h).
- Culture and mass production are simple and relatively inexpensive.
- Without degrading their infectivity, they can be stored for several weeks to months.
- Able to infect a variety of soil-dwelling insect species (mainly lepidopterans) (Griffin et al. 1990)
- Adaptable to a variety of application methods and are human-friendly during application.

Conclusions

The most notable and damaging species of cutworms such as *A. ipsilon*, *A. segetum* and *A. flammatra* are recorded, which can cause extensive damages to economic crops. This insect can complete up to 4 generations during summer- or warmer-humid areas per year. In contrast, they pass through larval and pupal diapause in cooler areas and rarely complete only 1–2 generations per year. To manage this pest completely and economically, it is necessary to integrate different management tactics. EPNs provide the best alternate under the biological control of cutworms that kill insects within a short period (24–48 h). *S. carpocapsae* and *H. bacteriophora* are the effective species that killed most soil-dwelling insect pests and attracted commercial interest worldwide. However, these nematodes are an eco-friendly and IPM compatible practice, which is an excellent alternative to chemical insecticides for managing cutworms. In addition to this, there is a special need to isolate more indigenous EPN species against the target species of cutworms for its efficient management.

Future prospects

Various in vitro and field studies claimed the *Steinernema* spp. and *Heterorhabditis* spp. as practical and potential biological control agents of cutworm, *Agrotis* spp. throughout the world. The symbiotic bacteria (*Xenorhabdus* and *Photorhabdus*) are quite efficient in their mode of action as insecticidal. The future of EPNs as potential biopesticides is promising. Their success is laced with the innovative ideas of incorporating EPN methodologies in different fields of study. Progressive advances in analysis

Table 2 Studies on management of *Agrotis* spp. in India and abroad

Insect species	Host plant	Place of occurrence	EPNs	References
A. ipsilon	In vitro	Colorado, western USA	*S. feltiae*, *S. bibionis* and *H. heliothidis*	Capinera et al. (1988)
A. ipsilon	Potato	Florida	*S. feltiae*	Georgis et al. (1989)
A. ipsilon	Maize	–	*S. carpocapsae*	Levine and Oloumi-Sadeghi (1992)
A. ipsilon	Carrot	Japan	*S. carpocapsae*	Yokomizo and Kashio (1996)
A. ipsilon	In vitro	California, USA	*S. carpocapsae*	Baur et al. (1997)
A. ipsilon, *A. segetum*	Turnip	India	*S. bicornutum*, *S. carpocapsae*, *H. indica*	Hussaini et al. (2000)
A. ipsilon	Potato	India	*S. riobrave*	Mathasoliya et al. (2004)
A. ipsilon	All vegetables	Florida, USA	Steinernematids and Heterorhabditis	Seal et al. (2010)
A. segetum	In vitro	Himachal Pradesh, India	*H. bacteriophora*	Chandel et al. (2010)
A ipsilon	Turfgrass	–	*H. bacteriophora*, *S. carpocapsae*, *S. feltiae*, and *S. riobrave*	Ebssa and Koppenhofer (2011)
A. ipsilon	Turfgrass	USA	*H. megidis*, *H. bacteriophora*, *H. bacteriophora*, *H. megidis* and *S. riobrave*	Ebssa and Koppenhofer (2012)
A. ipsilon	In vitro	India	*H. bacteriophora*	Mantoo et al. (2012)
A. ipsilon	In vitro	–	*S. carpocapsae*	Khattab and Azazy (2013)
A. ipsilon	Turfgrass	Canada	*S. carpocapsae*	Bélair et al. (2013)
A. ipsilon	Chinese cabbage, *Brassica rapachinensis* L	China	*S. carpocapsae* Mex and *H. indica* LN2	Yan et al. (2014)
A. ipsilon	Turfgrasses	Korea	*S. carpocapsae* GSN1 Strain	Lee and Potter (2015)
A. ipsilon	Turf, vegetables	–	*S. carpocapsae*	Gozel and Gozel (2016)
A. ipsilon	In vitro	Egypt	*S. glaseri* and *H. bacteriophora* Poinar (HP88 strain)	Hassan et al. (2016)
Turnip moth, *A. segetum*	Vegetables	Himachal Pradesh, India	*H. indica*	Vashisth et al. (2018)
A. ipsilon	In vitro	Turkey	*H. bacteriophora* FLH-4-H, *H. indica* 216-H, *S. carpocapsae* E76-S	Yuksel and Canhilal (2018)
A. ipsilon	In vitro	Egypt	*S. monticolum* and *H. bacteriophora*	Sobhy et al. (2020)
A. ipsilon	Potato	Jorhat, Assam	*H. bacteriophora*	Devi et al. (2021)

and study on EPNs promote the extensive use of EPNs in field conditions. It would be an effective tool for managing insects with resistance to pesticides, economical for farmers, and advantageous to the environment.

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