Management of lepidopteran insect pests through entomopathogenic nematodes: An overview

Abstract: Lepidopteran pest cause significant loss in quantity and quality of produced in many agricultural and horticultural crops. Therefore management strategies should aim to reduce their population below threshold level. Though chemical pesticides are recommended for controlling these insect pests, biocontrol agents are mostly recommended in IPM programme. The most important bio-control agent is the entomopathogenic nematodes (EPNs). This review discusses the bioefficacy of some of important species of entomopathogenic nematodes against various lepidopteran insect pests.

Key words: Entomopathogenic nematodes (EPNs), biocontrol agent, lepidopteran insect, Steinernema spp., Heterorhabditis spp.

INTRODUCTION

Insect pest cause significant yield loss and reduction in quality of produced in many agricultural and horticultural crops. Lepidopteran insects are one of the most widely distributed and destructive insect pests in the world, comprise about 180,000 species with 126 families and 46 super families (Heppner, 2008; Jim, 2011). The female may produce eggs as high as 30,000 eggs per day which may create substantial problems for agricultural crops (Denlinger, 2009). This necessitates the development of management strategies to reduce their population below threshold level. Chemical control is recommended to reduce their population. But biocontrol agents are alternate strategy which provides good health and pollution free environment and mostly recommended in IPM programme. The most important biological control agent is the Entomopathogenic nematodes (EPNs) which have significant potential in management of many insect pests (Dutky & Hough, 1955; Georgis & Gaugler, 1991). EPNs have many positive characteristics like wide host range, host searching ability, short life cycles, easy mass culture and application, and good persistence etc. (Bari and Kaya, 1984; Kaya and Gaugler, 1993; Lacey et al., 2000; Grewal et al., 2005; Shapiro-Ilan & Gaugler, 2019).

Bioefficacy of entomopathogenic nematodes (EPNs) against some of the important lepidopteran insect pests:

The greater wax moth (Galleria mellonella L.) is an important pest of beekeeping industry (Anwar et al., 2014), but it is used as a standard host for observations on virulence of many biological control agents like EPNs (De Doucet et al., 1999; Hendrichs et al., 2009; Kulkarni et al., 2012).

The tomato leafminer (Tuta absoluta) is one of the most important pests associated with tomato. Damage produced by this insect is focused on the larval galleries made on the leaves, the terminal buds, the flowers and the fruits of the tomato crops. Tomato leafminer larvae produce tunnels generating big entry holes to the galleries that can be effortless used by nematodes to penetrate and avoid desiccation and ultraviolet light and finally infect the larvae.

Potato tuber moth (PTM) (Phthorimaea operculella) is a pest of solanaceae crops which contributes to potato loss in field and storage. PTM larvae attack leaves, petioles and stems and infest tubers during plant senescence. Severe damage (up to 100% in some cases) can occur in storage. The susceptibility of PTM to EPN infection depended on different factors such as the developmental stage of insect, the age of the host insect within a given stage, soil type, EPN species/strain and IJ concentration as well as foraging behavior. The overlap between generations
of PTM result in high populations providing suitable conditions for use of EPNs (*S. carpocapsae* and *H. bacteriophora*) against larval and prepupal stages of PTM during the growing season (Yathom 1986; Gaugler 2002).

The diamondback moth (DBM) (*Plutella xylostella*) attacks and damages cruciferous. Enhanced control of insect larvae by entomopathogenic nematodes on leaves can be obtained by use of anti-desiccants (Glazer et al., 1992; Mason & Wright, 1997) and optical brighteners (Ratnasinghe, 1996).

The fall armyworm (FAW), (*Spodoptera frugiperda*) is a polyphagous pest of maize and other Poaceae crops. When *S. frugiperda* larvae are lodged inside the corn whorl the deposition of the leaves prevents the direct contact with other organisms and reduces the larval control. Caccia et al., (2014) reported the FAW’s susceptibility to EPNs. Acharya *et al.*, (2020) investigated the effectiveness of *H.indica*, *S. carpocapsae*, *S. arenarium* and *S. longicaudum* against various stages of the FAW larvae. They found that younger larvae (e.g., first, second and third-instar larvae) of the FAW were more susceptible to *H.indica* and *S. carpocapsae*, while elder larvae (e.g., 4th, 5th and 6th larval instars) were susceptible to *S. arenarium* and *S. longicaudum*.

Corn earworm, (*Helicoverpa zea*) attacks corn and other cultivated and wild host plants. *H. zea* causes damage primarily by tunneling into the ear in corn. This insect feeds primarily on the fruit of its hosts and, in corn, usually feeds first on the silks and then channels downward into the ear. Once larvae enter the silk channel of the corn fruit, they are well protected, allowing high survival. Control strategy should be focused on the prepupal and pupal stages of corn earworm populations in the soil, for preventing adult emergence and subsequent migration. Cabanillas and Raulston (1995) observed that timing soil applications of *S. riobravis* with the life cycle of the target insect is a key efficacy factor. *H. zea* mortality was obtained (100 and 95%) by applying the nematodes when 50% of the larvae were late instars and still in the maize ears, and when 10% of the larvae had left the ears to pupate in the soil. Cabanillas and Raulston (1996) demonstrated that irrigation method, timing and nematode concentration were important factors in the success of the nematode. Application of *S. riobrave* (2 lakhs IJs/m²) resulted in 95% insect mortality when applied via in-furrow irrigation compared with 84 and 56 % mortality when applied after or before surface irrigation, respectively.

Brinjal shoot and fruit borer, (*Leucinodes orbonalis*) the damage is observed initially on the plant shoots prior to flowering and later on the fruits. Timing of application of EPNs with the lifecycle of the target insect is a key factor to increase efficacy. Larvae infesting flowers and those that have fallen onto the soil prior to pupation are targeted for control by EPNs. Factors such as temperature and sunlight are reported to affect the activity of IJs (Gaugler and Bousch,1978; Gaugler et al.,1992; Grewal et al.,1994).Spraying of IJs at dusk is reported to reduce the negative effects of sunlight by maintaining high RH(Lello et al.,1996).

Pink bollworm (PBW), (*Pectinophora gossypiella*) is one of the most serious pests of cotton. *P. gossypiella* is excellent target for the use of EPNs in cotton. Although pink bollworm pupae are not susceptible to EPNs (Henne berry et al.,1995), the diapausing larvae in soil during the winter are susceptible (Gouge et al.,1999).Due to lower temperature during winter, *H.bacteriophora* has been found to be more effective than *S.riobraive* for the control of pink bollworm (Gouge et al.1999).

Codling moth (CM), (*Cydia pomonella*) a serious pest of apple and pear.CM overwinters in cryptic habitats as cocooned diapausing larvae. Their elimination or significant reduction at this stage would provide complete or substantial protection to fruit early in the following growing season. Studies by Kaya et al. (1984), and Unruh and Lacey (2001) elucidated the importance of
moisture for control of CM by *Steinernema carpocapsae*. Cryptic habitats, such as those used by CM for their overwintering sites (under loose bark, in litter at the base of trees, in nearby woodpiles, fruit bins and the like) may also provide favorable environmental conditions for entomopathogenic nematodes (EPNs) (Begley, 1990; Koppenhofer et al., 2020). Used under optimal conditions of warm temperatures and available free water, EPNs can be effective control agents of cocooned CM larvae in orchards (Kaya et al., 1984; Lacey et al., 2000; Nachtigall & Dickler, 1992; Sledzevskaya, 1987; Unruh & Lacey, 2001) and fruit bins (Cossentine et al., 2002; Lacey and Chauvin, 1999; Lacey et al., 2005). Navaneethan et al., 2010 reported that efficacy of *S. feltiae* against the diapausing CM larvae by using a surfactant-polymer formulation.

**Factors affecting efficacy of entomopathogenic nematodes**

The efficacy of EPNs is governed by their virulence and their capability to find out their hosts. Nematode strains differ in virulence to insect host and that various ages and stages of host insects differ in susceptibility (Kaya, 1985). EPNs can effectively control several lepidopteran species (Kaya 1985; Siegel et al., 2004; Batalla-Carrera et al., 2010; Negrisoli et al., 2010) but matching the most suitable nematode with the target host is a critical component for success in any biocontrol programme (Shapiro-Ilan and Cottrell, 2006).

Factors such as temperature and sunlight are reported to affect the activity of IJs (Gaugler and Bousch, 1978; Gaugler et al., 1992; Grewal et al., 1994). Spraying of IJs at dusk is reported to reduce the negative effects of sunlight by maintaining high RH (Lello et al., 1996). The use of local isolates, which are adapted to local temperatures, was reported to give a high level of efficacy against the target pest (Mason and Wright, 1997).

Timing of application of entomopathogenic nematodes with the life cycle of the target insect is a key factor to increase efficacy (Hussaini and Singh, 1998). Pre and post application irrigation is essential for nematode movement, persistence, and infection (Koppenhofer et al., 2020). These factors and the irrigation of the field before and after spraying contributed to the effectiveness of EPNs against target pests. Application volume vary with soil type, compaction, structure, crop, target insect, target insect behavior, formulation and plant architecture. Berg et al. (1987) suggested application volumes between 935 L ha⁻¹ and 2800 L ha⁻¹ with entomopathogenic nematodes to pasture for controlling subterranean insect pests. The quantity of infective juveniles (IJ) for application in the field varies according to the crop, target insect, formulation and application technology (up to 2.5 billion infective juveniles ha⁻¹) (Garcia et al., 2008).

Entomopathogenic nematodes can be applied with equipment developed for pesticides, including backpack, boom (with or without air assistance), aerial, and electrostatic sprayers (Georgis, 1990).

Entomopathogenic nematodes have been used with variable success against lepidopteran pests, including those found in the soil, in cryptic habitats, on foliage (Batalla-Carrera et al., 2010). Sensitivity to low moisture, high temperature and ultraviolet radiation has limited nematode use against foliage-feeding insects. However, most success has been achieved in insect pests that spend some stages in the soil or those in cryptic habitats such as galleries in plants where infective juveniles (IJ) are protected from environmental extremes (Shapiro-Ilan et al., 2002; Almeida et al., 2007). *S. feltiae* and some other steinernematids have far better potential for insect control in soil and other cryptic habitats because of their dependence on moisture, their ability to search for a host over short distances, and their ability to invade the host through body openings without having to be ingested (Gaugler, 1981).

The stage of insect development has a significant effect on vulnerability to EPNs (Kaya & Hara, 1980; Kaya & Grieve 1982; Kaya, 1985). *Spodoptera exigua* (Hubner), prepupa was the most
susceptible stage, showing the highest mortality across all EPNs concentrations. It seems that developmental events during the pupal stage might influence infective juvenile penetration rates (Dolinski et al., 2006). Acharya et al. (2020) reported that younger larvae (e.g., first-, second- and third-instar larvae) of the Fall armyworm (FAW) were more susceptible to *H. indica* and *S. carpocapsae*, while elder larvae (e.g., 4th, 5th and 6th larval instars) were susceptible to *S. arenarium* and *S. longicaudum*.

**Conclusion**

Various successful field studies advocate the potential of entomopathogenic nematodes against lepidopteran insect pests and their widespread uptake on the biocontrol market. The effectiveness of EPNs can also be improved by genetic improvement through selection and transgenic methods, time and method of application.

**Table.1. Bioefficacy of entomopathogenic nematodes against lepidopteran insect pests.**

| Pest | Nematode | Laboratory/field experiment | Efficacy | Reference |
|------|----------|------------------------------|----------|-----------|
| Wax moth (*Galleria mellonella*) | *Heterorhabditis bacteriophora*<br>*Steinernema glaseri*<br>*S. scarabaei*<br>*S. feltiae*<br>*H. megidis*<br>*S. carpocapsae*<br>*H. heliothidis*<br>*S. glaseri*<br>*S. surkhetense*<br>*S. feltiae DDKB-17*<br>*H. bacteriophora AVB-15*<br>*H. indica* | Lab | 87%-100% | Hyrs1,2011; Rahoo et al.,2018<br>Saunders & Webster, 1999<br>Zervos et al.,1991<br>Trinh et al.,2021<br>Yuksel & Canhilal, 2019 |
| *Galleria mellonella,* *Helicoverpa armigera* *Spodoptera litura* | *S. abbasi* CS38 | Lab | 100% | Heena et al.,2021 |
| *Galleria mellonella,* *Corcyra cephalonica* *Helicoverpa armigera* *Spodoptera litura* *Scirpophaga excerptalis* *Sesamia inferens* *Chilo sacchariphagus indicus* | *S. glaseri*<br>*S. feltiae*<br>*H. indicus* | Lab | | Karunakar et al.,1999 |
| *Spodoptera litura,* *S. siamkayai* | Lab | | | Adiroubane et al., |
| **Plutella xylostella**, Leucinodes orbonalis, Earais vitella, Cnaphalocrocis medinalis. | S.carpocapsae | Lab | 2010 |
|---|---|---|---|
| **Galleria mellonella** Spodoptera litura | S.carpocapsae | Lab | Fuchi et al.,2016 |
| **Spodoptera exigua** Harrisinia brillians pupae | N.carpocapsae | Lab | Kaya & Hara, 1980;1981 |
| Wax moth (Galleria mellonella), Pink bollworm (Pectinophora gossypiella), Eggplant fruit borer (Leucinodes orbonalis) Armyworm (Spodoptera litura) | S.kraussei | Lab | Khan et al.,2020 |
| **Cabbageworm (Artogeia rapae)** Diamondback moth (Plutella xylostella) Cabbage looper (Trichoplusia ni) | S. carpocapsae All S.feltiae UK S. feltiae 27 S. riobrave 335 | Lab | Belair et al.,2003 |
| Tomato leafminer (Tuta absoluta) | S.carpocapsae All | Lab, greenhouse | Sabry et al.,2016 |
| | S.carpocapsae S. feltiae H.bacteriophora | | Van Damme et al., 2016 |
| | S. feltiae | Field | Williams &Walters, 1999 |
| *Heterorhabdities* sp. S. karii | Lab | Mutegei et al.,2017 |
| S. yirgalemense 157-C S.jeffreyense | Lab | Dlamini et al.,2020 |
| S.carpocapsae, B14 S. feltiae Bpa H.bacteriophora DG46 | Lab, greenhouse | Batalla-Carrera et al., 2010 |
| S.affine 46 S. carpocapsae 1133, | Field | Gozel & Kasap ,2015 |
| Insect                          | Species/Strain                          | Reduction of plant damage | Reference                                  |
|--------------------------------|-----------------------------------------|---------------------------|--------------------------------------------|
| Stem borer (Sesamia calamistis) | H. bacteriophora S. feltiae             | 4%-57%                    | Claudius-Cole, 2018                        |
| Turnip moth (Agrotis segetum | H. indica H. bacteriophora               | 93.33%                    | Vashisth et al., 2018                      |
| Red-backed cutworm (Euxoa ochrogaster) | S. feltiae H. bacteriophora       | 33%-70%                   | Morris, 1985                               |
| Army cutworm (Euxoa auxiliaries) | S. carpcapsae H. bacteriophora         | 100%                      | Hussaini et al., 2000                      |
| Pale western cutworm (Agrotis orthogonia) | S. carpcapsae H. bacteriophora   | 33%-70%                   | Mathasoliya et al., 2004; Yuksel & Canhilal, 2018; Hassan et al., 2016; Shairra et al., 2016 |
| Black army cutworm (Actebia fennica) | S. carpcapsae H. bacteriophora         | 33%-70%                   | Yuksel et al., 2018                        |
| Bertha armyworm (Mamestra configurata) | S. carpcapsae H. bacteriophora         | 33%-70%                   | Hussaini et al., 2000                      |
| Oriental fruit moth (Grapholita molesta) | S. rarum RS69 H. bacteriophora RS33 | 94% - 97.0%               | Negrisolli et al., 2013                    |
| Peachtree borer, (Synanthedon exitiosa) (S. pictipes) | H. heliothidis S. carpcapsae H. bacteriophora | 80%                      | Cossentine et al., 1990; Cottrell & Shapiro-Ilan, 2006; Shapiro-Ilan et al., 2009-2010; 2015; 2016; 2016a |
| Currant borer moth, (Synanthedon) | N. bibionis Steinernema sp.            | 90%                       | Deseo & Miller, 1985; Kaya                |
| Insect/Plant Pathogen | Trichogramma Species | Location | Efficiency | Reference |
|-----------------------|----------------------|----------|------------|-----------|
| Grape root borer (Vitacea polistiformis) | H. indica | Lab Greenhouse | 82.73% | Williams et al., 2002 |
| Grape root borer (Vitacea polistiformis) | S. glaseri | Lab | | |
| Rice meal moth (C. cephalonica), Spodoptera litura, Helicoverpa armigera, Plutella xylostella, Leucinodes orbonalis, Earias vittella, Orthaga exvinascea, Eublemma versicolor, Papilio polytes, Exelastis atomosa, Hymenia recurvalis | H. indica, S. glaseri | Lab | 82.73% | Kamaliya et al., 2019 |
| S. litura (3rd, 4th, 5th instar larvae) | H. indica | Lab | 82.73% | Kamaliya et al., 2019 |
| S. litura (3rd, 4th, 5th instar larvae) | H. indica PBCB | Lab | 88.67% | Caoili et al., 2018 |
| S. litura (3rd, 4th, 5th instar larvae) | Steinernema sp. 64-2, S. carpocapsae A24, S. carpocapsae All, S. carpocapsae G-R3a-2, S. longicaudum X-7, H. indica 212-2 | Lab | 100% | Yan et al., 2020 |
| Rice moth (Corcyra cephalonica) (5th instar larvae) Black cutworm (Agrotis ipsilon) (4th instar larvae) Silkworm (Bombyx mori) (5th instar larvae) | H. bacteriophora, S. carpocapsae | Lab | 100% | Zaki et al., 2000 |
| Brinjal shoot and fruit borer, (Leucinodes) | S. carpocapsae PDBC -11 | Field | | Ganga Visalakshy et al., 2009 |
| Insect Species                                      | Steinernema Species | Cultivation Method | Mortality Rate         |
|-----------------------------------------------------|---------------------|--------------------|------------------------|
| orbonalis)                                          | Steinernema sp. H.indica |                    | Hussaini et al.,2002   |
| Spodoptera frugiperda, Helicoverpa gelotopoeon       | S.diaepresi         | Lab                | Milena et al.,2014     |
| Fall armyworm (Spodoptera frugiperda) (1st,3rd,5th instar, pupa) | S.feltiae All, Mexican (DD-136 x Breton) S. bibionis. | Lab | 7%-20% Fuxa et al.,1988 |
| Spodoptera litura (pre pupa, pupa ,adult)           | S.feltiae           |                    | Narayan & Gopalkrishna, 1987. |
| S. litura                                           | H. indica           | Lab                | Acharya et al.,2020     |
| S. glaseri                                          | H. bacteriophora    |                   | Kondo & Ishibashi , 1986;1986a;1987;1988     |
| S. carpocapsae                                      | S. bibionis         |                   | Gouge et al.,1996;1999  |
| S. longicaudum                                      | S. glaseri          |                   | Umamaheswari et al. 2006. |
| Spodoptera litura, Galleria mellonella              | S. feltiae (DD-136) (=N. carpocapsae) S. bibionis S. glaseri | Lab | 50.6%-75.6% Sezhian et al.,1996 |
| Pectinophora gossypiella (Late instars), Heliothis virescens, Trichoplusia ni, Spodoptera exigua | S. riobrave S. carpocapsae Kapow H.bacteriophora Cruiser | Lab | 92%-100% Atwa & Hassan, 2014 |
| Spodoptera litura                                   | H.indica            | Glasshouse Microplot | 50.6%-75.6% Umamaheswari et al. 2006. |
| Spodoptera litura (4th instar larvae)               | S.carpocapsae       | Field              | 95% Sezhian et al.,1996 |
| Spodoptera litura                                   | H.indica            | Lab                | 50% Dichusa et al.,2021 |
| H. armigera                                         | S. glaseri          | Greenhouse         | Patel & Vyas, 1995     |
| Spodoptera litura (3rd instar larvae)               | S.carpocapsae       |                    | Raveendranath et al., 2007 |
| Armyworm, (Spodoptera litura)                       | S.pakistanense      | Lab                | 74%-95% Javed et al.,2022 |
| Spodoptera littoralis (3rd instar larvae)            | H.bacteriophora HP88 S.glaseri NJ | Lab | 92%-100% Atwa & Hassan, 2014 |
| Insect                          | Nematode                          | Location | Percentage | References                          |
|--------------------------------|-----------------------------------|----------|------------|--------------------------------------|
| Spodoptera littoralis          | H. taysearai                       | Lab      | 60%-90%    | Abd El Azim, 2022                   |
| S. littoralis G. mellonella    | Heterorhabditis sp. ELG           | Lab      | 61.4%-100% | Abdel-Razek & Abdelgawad, 2007      |
| Spodoptera littoralis (2nd, 3rd, 4th, 5th, 6th instar larvae), Plutella xylostella (2nd, 3rd, 4th instar larvae), Pieris rapae (2nd, 5th instar larvae) | S. carpocapsae All S. carpocapsae S2 H. indicus SAA2 H. bacteriophora HP88 | Lab | | Salem et al., 2007 |
| Cabbage worm (Pieris rapae)    | H. taysearai                       | Lab      | 55-100%    | Saleh, 1995                         |
| Cabbage butterfly, (Pieris brassicae) | H. pakistanensis                 | Field    | 61.16%     | Askary & Ahmad, 2020                |
|                                | S. feltiae HR1 H. bacteriophora HR2 | Lab      | 12% - 72.08% | Kasi et al., 2021                   |
| Spodoptera littoralis, Agrotis ipson | H. bacteriophora BA1 S. carpocapsae BA2 | Lab | 100% | Saleh & Ragab, 1999; Saleh et al., 2015. |
| Spodoptera littoralis, Agrotis ipson | S. monticulum H. bacteriophora | Lab | 97.77%-100% | Sobhy et al., 2020                  |
| Black cutworm (Agrotis ipson)  | Steinernema feltiae (= Neoaplectana carpocapsae) Mexican Kapow, S. bionis, H. heliothis | Field | 50% reductio n in plant damage | Capinera et al., 1988         |
| Turnip moth (Agrotis segetum)  | S. carpocapsae                     | Lab      |            | Ebrahimi et al., 2019               |
| Agrotis ipson Galleria mellonella | S. carpocapsae HB310             | Lab      | 90.48% 82.33% | Nangong et al., 2021               |
| Cotton leafworm, (Spodoptera littoralis) Black cutworm, (Agrotis ipson) | Heterorhabditis sp. TAN5 | Lab | 24 %-100% 18%-96% | Nouh, 2021 |
| Insect Species | Species of Parasite | Test Condition | Percentage | Publication |
|---------------|---------------------|----------------|------------|-------------|
| Black cutworm (*Agrotis ipsilon*) | *S. carpocapsae* | Field | Levine & Oloumi-Sadeghi, 1993 |
| Tobacco cutworm, (*Spodoptera litura*) | *S. carpocapsae* PC, *H. bacteriophora* HY, *S. monticola* CR | Lab | 100% | Park et al., 2001 |
| *Spodoptera litura* | *H. bacteriophora* | Lab | Baweja & Sehgal, 1997 |
| *Spodoptera litura, Spodoptera frugiperda* | *H. indica*, *S. carpocapsae* | Lab | Acharya et al., 2020; 2020a |
| *Spodoptera frugiperda*, *Heliothis zea* | *S. feltiae* | Lab | Richter and Fuxa, 1990 |
| Indianmeal moth (*Plodia interpunctella*) | *H. bacteriophora* HP88, Lewiston, Oswego, *H. indica* Homl, *H. marelatus* Point Reyes, *H. megidis* UK211, *H. zelandica* NZH3 | Lab | 44% | Mbata & Shapiro-Ilan, 2005 |
| European corn borer, (*Ostrinia nubilalis*) | *N. carpocapsae* DD-136 | Lab, Field | Lewis & Raun, 1978 |
| Corn earworm (*Helicoverpa zea*), Fall armyworm (*Spodoptera frugiperda*) (prepupae and pupae) | *S. sp.* | Field | 49.4 - 46.1% parasitization | Raulston et al., 1992 |
| Fall armyworm (*Spodoptera frugiperda*) | *S. carpocapsae* | Lab | 28% | Espky & Capinera, 1993; 1994 |
| *Spodoptera frugiperda* | *S. arenarium* All *Heterorhabditis* sp., RSC02, *S. sp*. IBCP-n6, *H. indica* | Lab, Greenhouse, Field | 77.5 and 87.5% | Garcia et al., 2008; Andalo et al. 2010 |
| Fall armyworm (*Spodoptera frugiperda*) (2nd and 5th larval instars) | *H. indica* AUT 13.2, *S. siamkayai* APL 12.3 | Lab, Greenhouse, Field | 33%-83% | Wattanachaiyingsroen, 2021 |
| Fall armyworm (*Spodoptera frugiperda*) | *S. carpocapsae* | Lab | 35% | Viteri et al., 2018 |
| *S. frugiperda* | *H. indica*, *S. carpocapsae*, *S. glaseri* | Field | Negrisol et al., 2010 |
| Common Name | Species | Life Stage | Area | Efficiency | References |
|-------------|---------|------------|------|------------|------------|
| **Spodoptera frugiperda, Helicoverpa gelotopoeon** | *S. diaprepesi* | Lab | | | Caccia et al., 2014 |
| **Cotton bollworm (Helicoverpa armigera)** | *S. feltiae* | Lab, Glasshouse | 75%-90% | Glazer & Navon, 1990; Glazer 1997; Navon et al., 2002; Shahina et al., 2014; Ebrahimi et al., 2018 |
| **Corn earworm, Helicoverpa (=Heliothis) zeae** | *S. riobravis*, *S. carpocapsae* | Field | 90% | Cabanillas & Raulston, 1994; 1995; 1996; 1996a; 1996 |
| **Corn earworm, (Heliothis zeae)** | *N. carpocapsae DD-136* | Field | 58%-88% | Bong & Sikorowski, 1983; Bong 1986 |
| **Pink bollworm (Pectinophora gossypiella)** | *S. carpocapsae* | | | Lindegren et al., 1993 |
| | *S. riobrave*, *H. bacteriophora HP88* | Lab | 76.43%-86.45% | Shairra & Nouh, 2014; Shairra et al., 2016 |
| **Pink bollworm, (Pectinophora gossypiella) Cabbage looper (Trichoplusia ni) Beet army worm (Spodoptera exigua)** | *S. carpocapsae*, *S. riobravis* | Lab, Field | 92.5%-100% | Henneberry et al., 1995; 1995a; 1996; 1996a |
| **Pink bollworm, (Pectinophora gossypiella)** | *S. riobravis* | Field | 25.7%-92.4% | Jech & Henneberry, 1997 |
| **Codling moth (Cydia pomonella) (diapausing larvae)** | *S. carpocapsae Sal*, *S. feltiae Umea*, *S. riobrave* | Lab, Field | 94.4%-94.7% | Dutky and Hough, 1955; Kaya et al., 1984; Nachtigall & Dickler, 1992; Lacey & Unruh, 1998; Lacey & Chauvin, 1999; Vega et al., 2000; Unruh, & Lacey, 2001; Lacey et al., 2005; 2006; De Waal et al., 2017; 2018 |
| **Codling moth (Cydia pomonella)** | *S. feltiae*, *S. carpocapsae*, *S. yirgalemense* | | | Sledzevskaya, 1987; Cossentine et al., 2002 |
| Species/Host | Effectiveness | Method | Reference |
|-------------|---------------|--------|-----------|
| *H. zealandica* | Field | 43.85 - 86.27% | Lacey *et al.*, 2000; 2006a; Malan *et al.*, 2011; DeWaal, 2008; De Waal *et al.*, 2010, 2011a, b, 2013; Odendaal *et al.*, 2015; 2016; Ahmad *et al.*, 2020 |
| *H. pakistanensis* | Field | 43.85 - 86.27% | Lacey *et al.*, 2000; 2006a; Malan *et al.*, 2011; DeWaal, 2008; De Waal *et al.*, 2010, 2011a, b, 2013; Odendaal *et al.*, 2015; 2016; Ahmad *et al.*, 2020 |
| *S. carpocapsae* Bakişli | Lab | 71.5% - 82.63% | Yagci *et al.*, 2021 |
| *H. bacteriophora* TOK20 | Lab | 71.5% - 82.63% | Yagci *et al.*, 2021 |
| *H. bacteriophora* 11-KG | Lab | 71.5% - 82.63% | Yagci *et al.*, 2021 |
| Filbertworm, (*Cydia latiferreana*) | *S. carpocapsae* | Lab, Field | 65% - 92% | Chambers *et al.*, 2010 |
| Carob moth (*Ectomyelois ceratoniae*) | *S. carpocapsae* *S. feltiae* | Lab | 76.5% - 79.75% | Memari *et al.*, 2016 |
| Diamond backmoth (*Plutella xylostella*) | *S. carpocapsae* All *S. riobravis* | Lab, greenhouse, Field | 79.1% | Baur *et al.*, 1997; 1998; Shinde & Singh, 2000; Singh & Shinde, 2002 |
| *S. carpocapsae* | Lab | Ratnasinghe & Hague, 1997; Schroer & Ehlers, 2005; Schroer *et al.*, 2005 |
| *H. indica* | Lab | 86.7% - 96.0% | Nyasani *et al.*, 2008; 2008a |
| *S. karii* | Lab | 86.7% - 96.0% | Nyasani *et al.*, 2008; 2008a |
| *S. wesieri* | Lab | 86.7% - 96.0% | Nyasani *et al.*, 2008; 2008a |
| *S. carpocapsae* | Lab | 72.6% - 96% | Zolfagharian *et al.*, 2016 |
| *H. bacteriophora* | Lab | 72.6% - 96% | Zolfagharian *et al.*, 2016 |
| *H. bacteriophora* BA1 | Lab | 72.6% - 96% | Zolfagharian *et al.*, 2016 |
| *S. carpocapsae* BA2 | Greenhouse | 64.4% - 79.8% | Hussein *et al.*, 2015 |
| Potato tuber moth, (*Phthorimaea operculella*) (second, fourth instar larvae, prepupa) | *S. carpocapsae* *S. feltiae* *S. glaseri* *S. bibionis* *H. bacteriophora* | Lab | Ivanova *et al.*, 1994; Hassani-Kakhki *et al.*, 2013. |
| Insect Species                                      | Species Used                            | Location | Effectiveness       | Reference(s)                          |
|----------------------------------------------------|-----------------------------------------|----------|---------------------|---------------------------------------|
| Potato tuber moth, *Phthorimaea operculella*       | S. carpocapsae, S. feltiae, H. bacteriophora | Lab      | 40%-100%            | Lacey & Kroschel, 2009; Kepenekci et al., 2013 |
| Squash vine borer, *Melittia cucurbitae*           | Steinernema riobrave TX S. feltiae SN S. carpocapsae All S. carpocapsae Sal H. bacteriophora Hb H. sp. Hbl | Field   | 19%-61%             | Canhila & Carner, 2006                |
| Red hairy caterpillar, *Amsacta albistriga*        | Steinernema sp. H. indica               | Lab Microplot | 80% 42%          | Prabhu & Sudheer, 2008                |
| False codling moth, *Thaumatotibia Leucotreta*     | S. yirgalemense S. khoisanae H. zealandica H. bacteriophora | Lab Field | 93.5%-100%          | Steyn et al., 2017                   |
| False codling moth, *Thaumatotibia Leucotreta*     | S. yirgalemense H. zealandica S. litchii | Lab      | 93.5%-100%          | Steyn et al., 2017                   |
| *Dalaca pallens*                                   | S. australis QU N3 S. unicornum QU N13 | Lab      | 95%-100%            | Maldonado et al., 2012               |
| Sugarcane early shoot borer, *Chilo infuscatus*    | H. indica LN2 H. bacteriophora LN8 Heterorhabditis sp. HII S. carpocapsae S. glaseri S. riobravis S. feltiae | Lab      | 85%-95%             | Sankaranarayanan et al., 2011        |
| *Earias insulana Heliothis armiger* Spodoptera littoralis | S. carpocapsae Mexican                   | Field    | 85%-95%             | Glazer & Navon, 1989;1990 Glazer et al., 1991; 1992 |
| Mexican rice borer, *Eoreuma loftini*              | S. riobravis                            | Lab Field | 100%               | Legaspi et al., 2000                 |
| Brazilian apple leafroller, *Bonagota Salubricola* | H. bacteriophora RS107 H. bacteriophora RS57 | Lab Field | 61.1%-70.2%         | Negrisoli et al., 2010               |
| *Mocis latipes*                                    | H. bacteriophora                        |          |                    | Gonzalez-Ramirez et al., 2000        |
| *Ostrinia furnacalis H. armiger* S. litura         | S. abbasi MBLB S. minutum S. tami H. indica PBCB | Lab      | 28.15%-100%         | Caoili et al., 2018                  |
| *wax moth, Galleria mellonella*                    | S. carpocapsae S. glaseri               | Lab      |                    | Caroli et al., 1996                 |
| Specie                                                                 | Nematode isolate | Location | Efficacy | Reference                          |
|----------------------------------------------------------------------|------------------|----------|----------|------------------------------------|
| yellow meal worm, *(Tenebrio molitor)*                                | *S. feltiae*     | Lab      | 68%-100% | Kaya, 1985                         |
| beet armyworm, *(Spodoptera exigua)*                                  | *S. riobravis*   |          |          |                                    |
| black cutworm, *(Agrotis ipsilon)*                                    | *H. bacteriophora* |         |          |                                    |
| European corn borer, *(Ostrinia nubilalis)*                          |                  |          |          |                                    |
| *Spodoptera exigua*                                                  | *S. feltiae*     | Lab      | 68%-100% | Kaya & Grieve, 1982                |
| *Pseudaletia unipuncta*                                              | *N. carpocapsae* | Lab      | 4-57%   | Claudius-Cole, 2018                |
| Stem borer of maize *(Sesamia calamistis)*                           | *H. sp.*         | Lab      |          |                                    |
| Fall armyworm *(Spodoptera frugiperda)*                              | *S. carpocapsae* | All      | 1%-28%  | Espky & Capinera, 1994             |
| greater wax moth *(Galleria mellonella)*                            |                  |          |          |                                    |
| black cutworm *(Agrotis ipsilon)*                                    |                  |          |          |                                    |
| *Pseudaletia unipuncta*                                              | *H. bacteriophora* | Lab     |          | Rosa et al., 2002                  |
| *N. carpocapsae* DD-136                                              |                  | Lab      |          | Srinivas & Prasad, 1991           |
| Rice leaf folder, *(Cnaphalocrosis medinalis)*                       |                  |          |          |                                    |
| Ghost moth *(Hepialus californicus)*                                 | *H. hepialus*    |          | 72%      | Strong et al., 1996                |
| Navel orange worm *(Amyelois transitella)*                           | *S. carpocapsae* | Field    | 72%      | Siegel et al., 2004                |
| European corn borer, *(Ostrinia nubilalis)*                          | *N. carpocapsae* DD-136 | Lab, Field |          | Lewis & Raun, 1978                |
| Melonworm, *(Diaphania hyalinata)*                                   | *S. carpocapsae* |          |          | Shannag & Capinera, 1995           |

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