

Management of lepidopteran insect pests through entomopathogenic nematodes: An overview

Abstract: Lepidopteran pest cause significant loss in quantity and quality of produced. Therefore management strategies should aim to reduce their population below threshold level. Among the different biological control agents, entomopathogenic nematodes (EPNs) have significant importance, because they have many positive characteristics of an efficacious bio-control agent. This review discusses the control potential 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. Insects are classified in different groups. Among these groups, lepidopteran insects are one of the most widely distributed insect pests in the world. In this order, about 180,000 species are described with 126 families and 46 super families (Heppner, 2008; Jim, 2011). Several lepidopteran species are major destructive pests in agriculture. The female may produce eggs from 200 to 600, while in some species; it may go as high as 30,000 eggs per day and create substantial problems for agricultural crops (Denlinger, 2009). This necessitates the development of management strategies to control these insect pests. Control of destructive insect pests through biocontrol is an alternate strategy that helps to provide pesticide free foodstuffs without any environmental risk. Among the different biological control agents, Entomopathogenic nematodes (EPNs) have significant importance, because they have many positive characteristics of an efficacious bio-control agent (Dutky

& Hough, 1955; Georgis & Gaugler, 1991). EPNs have broad spectrum effectiveness with short life cycles, easy mass production, host finding ability and persistence etc. (Bari and Kaya, 1984; Kaya and Gaugler, 1993; Lacey et al., 2000; Grewal et al., 2005; Shapiro-Ilan & Gaugler, 2019).

Good control of lepidopteran pests of field crops has been obtained with EPNs.

- The greater wax moth, *Galleria mellonella* L. is a most important pest of beekeeping industry (Anwar *et al.*, 2014), but valued mainly for its leading role as an invented host due to the susceptibility to several biological control agents (Hendrichs *et al.*, 2009) and for reproduction of various bio-control agents (Kulkarni *et al.*, 2012) including EPNs. The study of De Doucet et al. (1999) suggested that larvae of *G. mellonella* can be used as a standard host for testing and comparing virulence of EPNs.
- The tomato leafminer, *Tuta absoluta* is one of the most important pests associated with tomato. Females of *T. absoluta* usually deposit their eggs on leaves. The four larvae instars live in tunnels in the inner leaf where they feed and develop. Pupae are principally found in the ground but may also occur on the tomato plant. 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 effortlessly used by nematodes to penetrate and avoid desiccation and ultraviolet light and finally infect the larvae.
- Potato tuber moth (PTM), *Phthorimaea operculella* (Zeller) is a primary 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 crops in both temperate and tropical countries. Under field condition DBM is difficult to control, because the larvae feed as leaf miners and then subsequently on the underside of the leaf surface where they are not easy to control. Enhanced control of insect larvae 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. Medium sized and large larvae damage corn and sorghum by feeding in the whorl of the plant or in corn ears, and they pupate in the soil. Younger larvae feed on the tissue of the leaves, while older ones cause severe defoliation. It also burrows into the growing point (bud, whorl, etc.), leading to dead heart, wilting and death of the unfurled leaves. 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* (= *Heliothis*) *zea* attacks corn and other cultivated and wild host plants. *H. zea* causes damage primarily by tunneling into the ear in corn. It is difficult to reduce populations of these insects satisfactorily once they have burrowed into the plant. 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. Thus, corn serves as a nursery crop to produce large adult populations that can migrate long distances to infest other susceptible crops such as cotton, sorghum, tobacco, and many vegetable crops. 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. riobrave* 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. The insect eggs are laid singly on the lower surface of leaves, mostly near the

lateral veins. On hatching, the larva enters the plant through the nodal region of the terminal or lateral bud, and feeds in a circular manner on the outer portion of the stem. This results in the death of the terminal portion of the shoot. Timing of application of EPNs with reference to the life-cycle 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* (Saunders), is one of the most serious pests of cotton. It bore into the squares or bolls within short time of hatching. Late instar PBW cut out of the boll and drop to the ground to enter diapause in the top few centimeters of soil, or remain in the bolls and diapause near or within the seeds. Also, final instar larvae overwinter as diapausing and damage the following season. *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.riobrave* for the control of pink bollworm (Gouge et al.1999).
- Codling moth (CM), *Cydia pomonella* a serious pest of apple and pear in most of the countries. In late spring, adults emerge and begin laying eggs when fruit is available. Neonate larvae enter the fruit and feed until full grown, and then exit as fifth instars in search of cryptic habitats in which to spin their cocoons and pupate. CM overwinters in cryptic habitats as

cocooned diapausing larvae. Thus, overwintering larvae represent the entire CM population in the fall, winter, and early spring. 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.

- The peachtree borer, *Synanthedon exitiosa* is a major pest of *Prunus* spp. including peach. The majority of *S. exitiosa* moths emerges and mates during late summer and early fall. Mated females deposit eggs on the bark of host plants, or sometimes on nearby non host plants. Hatched larvae bore into the trunk of stone fruit trees near the soil surface and tunnel into the roots. Larvae feed below the soil surface at the crown and on major roots. The larvae overwinter in the host plant, but can continue to feed during warm periods, and complete development in about one year.
- Carob moth, *Ectomyelois ceratoniae* is the most important and destructive polyphagous pest and causes damage on pomegranate, fig, pistachio, dates,

citrus, and almond. The larvae overwinter in fallen fruit or fruit left on trees and continue to develop inside the fruit. The first invasion of the pest occurs in early spring, concurrent with pomegranate flowering, and its activity is prolonged until the end of June or longer. The feeding larvae damage the pomegranates, providing a chance for saprophytic fungi penetration, such as *Aspergillus* spp. and *Penicillium* spp. The larvae feed in protected niches within the fruit, which is protected from the effects of insecticides.

- Filbertworm, *Cydia latiferreana* is a key insect pest associated with hazelnuts. Filbertworm larvae attack hazelnuts, when the neonates bore into developing nuts and feed on kernels. The final instars exit the nuts and overwinter in silken hibernacula on the ground or in the soil to a depth of 5-8 cm. Adults emerge after 10-15 d of pupation.
- False codling moth (FCM), *Thaumatotibia leucotreta* is an important pest of several citrus, deciduous, subtropical fruit and vegetables crops in most production areas in South Africa. FCM larvae burrow into the fruit and feeding-lesions diminish the marketability of the fruit.

Factors affecting efficacy

- 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; Negrisoni et al., 2010a) 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).
- Environmental factors: 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).

- Application methods and timing: Timing of application of entomopathogenic nematodes with reference to 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 varies 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 (IJs) 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 diverse pests, including those found in the soil, in cryptic habitats, on foliage, in manure, and in aquatic habitats (Batalla-Carrera *et al.*, 2010). Although 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 (IJs) 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 <i>Galleria mellonella</i>	<i>Heterorhabditis bacteriophora</i> <i>Steinernema glaseri</i> <i>S. scarabaei</i> <i>S. feltiae</i>	Lab		Hyrsl,2011; Rahoo et al.,2018
	<i>H.megidis</i> <i>S.carpocapsae</i>	Lab		Saunders & Webster, 1999
	<i>H. heliothidis</i> <i>S.glaseri</i>	Lab		Zervos et al.,1991
	<i>S. surkhetense</i>	Lab		Trinh et al.,2021
	<i>S. feltiae</i> DDKB-17 <i>H. bacteriophora</i> AVB-15	Lab	87%-100%	Yuksel & Canhilal, 2019
	<i>H.indica</i>	Lab		Khashaba et al.,2020
<i>Galleria mellonella</i> , <i>Helicoverpa armigera</i> <i>Spodoptera litura</i>	<i>S.abbasi</i> CS38	Lab	100%	Heena et al.,2021
<i>Galleria mellonella</i> , <i>Corcyra cephalonica</i> <i>Helicoverpa armigera</i> <i>Spodoptera litura</i> <i>Scirpophaga excerptalis</i> <i>Sesamia inferens</i> <i>Chilo sacchariphagus indicus</i>	<i>S.glaseri</i> <i>S. feltiae</i> <i>H.indicus</i>	Lab		Karunakar et al.,1999
<i>Spodoptera litura</i> , <i>Plutella xylostella</i> , <i>Leucinodes orbonalis</i> , <i>Earais vitella</i> , <i>Cnaphalocrocis medinalis</i> .	<i>S.siamkayai</i>	Lab		Adiroubane et al., 2010
<i>Galleria mellonella</i> <i>Spodoptera litura</i>	<i>S.carpocapsae</i>	Lab		Fuchi et al.,2016

<i>Spodoptera exigua</i> <i>Harrisinia brillians</i> pupae	<i>N.carpocapsae</i>	Lab	63% 55%	Kaya & Hara, 1980;1981
Wax moth (<i>Galleria mellonella</i>), Pink bollworm (<i>Pectinophora gossypiella</i>), Eggplant fruit borer (<i>Leucinodes orbonalis</i>) Armyworm (<i>Spodoptera litura</i>)	<i>S.kraussei</i>	Lab		Khan et al.,2020
Cabbageworm <i>Artogeia rapae</i> , Diamondback moth <i>Plutella xylostella</i> , Cabbage looper <i>Trichoplusia ni</i>	<i>S. carpocapsae</i> All <i>S.feltiae</i> UK <i>S. feltiae</i> 27 <i>S. riobrave</i> 335	Lab	75.7%- 100%	Belair et al.,2003
Tomato leafminer (<i>Tuta absoluta</i>)	<i>S.carpocapsae</i> All	Lab, greenho use	Percent of mine reductio n 12.9%.	Sabry et al.,2016
	<i>S.carpocapsae</i> <i>S. feltiae</i> <i>H.bacteriophora</i>		88.6 % 92.0% 76.3%	Van Damme et al., 2016
	<i>S. feltiae</i>	Field		Williams &Walters, 1999
	<i>Heterorhabditis</i> sp. <i>S. kari</i>	Lab		Mutegi et al.,2017
	<i>S. yirgalemense</i> 157-C <i>S.jeffreyense</i>	Lab	58.8% 46.4%	Dlamini et al.,2020
	<i>S.carpocapsae</i> , B14 <i>S. feltiae</i> Bpa <i>H.bacteriophora</i> DG46	Lab , greenho use	77.1%- 91.7%	Batalla-Carrera et al., 2010
	<i>S.affine</i> 46 <i>S. carpocapsae</i> 1133, <i>S. feltiae</i> 879 <i>H. bacteriophora</i> 1144	Field	39.3%- 90.7 %	Gozel & Kasap ,2015
Stem borer <i>Sesamia calamistis</i>	<i>H.bacteriophora</i> <i>S. feltiae</i>	Lab	4%- 57%	Claudius-Cole,2018
Turnip moth <i>Agrotis segetum</i> (L3,L5)	<i>H.indica</i> <i>H.bacteriophora</i>	Lab	93.33% 81.67%	Vashisth et al.,2018
Red-backed cutworm	<i>S. feltiae</i>	Lab		Morris, 1985

<i>Euxoa ochrogaster</i> army cutworm <i>Euxoa auxiliaries</i> pale western cutworm <i>Agrotis orthogonia</i> black army cutworm <i>Actebia fennica</i> Bertha armyworm <i>Mamestra configurata</i>	<i>H.bacteriophora</i>			
<i>Agrotis ipsilon</i> <i>A. segetum</i>	<i>S bicormutum</i> PDBC 2.1, 3.1, 3.2 <i>S.carpocapsae</i> PDBC 6.11, 6.61,13.1 <i>H indica</i> PDBC 6.71, 13.3	Lab	100%	Hussaini et al.,2000
<i>Agrotis ipsilon</i>	<i>S.riobrave</i> <i>S.carpocapsae</i> E 76-S <i>H.bacteriophora</i> FLH-4-H <i>H.indica</i> 216-H <i>H.bacteriophora</i> HP88	Field Lab	Reducti on of plant damage 10.92% 90%- 100%	Mathasoliya et al., 2004; Yuksel & Canhilal, 2018;2019 Hassan et al.,2016; Shairra et al.,2016
Variegated cutworm <i>Peridroma saucia</i>	<i>S.carpocapsae</i> <i>S.feltiae</i> <i>H.bacteriophora</i> <i>H.indica</i>	Lab	33%- 70%	Yuksel et al.,2018
Oriental fruit moth <i>Grapholita molesta</i>	<i>S.rarum</i> RS69 <i>H.bacteriophora</i> RS33	Lab, field	94% - 97.0%	Negrisola et al.,2013
Peachtree borer, <i>Synanthedon exitiosa</i> <i>S.pictipes</i>	<i>H.heliothidis</i> <i>S.carpocapsae</i> <i>H. bacteriophora</i>	Field	80%	Cossentine et al.,1990; Cottrell &Shapiro-Ilan, 2006;Shapiro-Ilan et al.,2009;2010;2015;2 016;2016a
Currant borer moth, <i>Synanthedon</i> <i>tipuliformis</i>	<i>N.bibionis</i> <i>Steinernema sp.</i>	Field	90%	Deseo & Miller, 1985; Kaya &Brown, 1986; Miller & Bedding, 1982; Miller,1989; Begley, 1990; Nachtigall & Dickler, 1992
Grape root borer <i>Vitacea polistiformis</i>		Lab Greenh ouse		Williams et al.,2002
Rice meal moth	<i>H. indica</i>	Lab		Sharmila et al.,2018

<i>C. cephalonica</i> <i>Spodoptera litura</i> <i>Helicoverpa armigera</i> <i>Plutella xylostella</i> <i>Leucinodes orbonalis</i> <i>Earias vittella</i> <i>Orthaga exvinascea</i> <i>Eublemma versicolor</i> <i>Papilio polytes</i> <i>Exelastis atomosa</i> <i>Hymenia recurvalis</i>	<i>S. glaseri</i>			
<i>S. litura</i> (3rd, 4th , 5th instar larvae)	<i>H.indica</i>	Lab	82.73%	Kamaliya et al.,2019
	<i>H. indica</i> PBCB	Lab	88.67%	Caoili et al., 2018
	<i>Steinernema</i> sp. 64-2 <i>S. carpocapsae</i> A24 <i>S. carpocapsae</i> All <i>S. carpocapsae</i> G-R3a-2 <i>S. longicaudum</i> X-7 <i>H. indica</i> 212-2	Lab	100%	Yan et al.,2020
Rice moth <i>Corcyra cephalonica</i> (5th instar larvae) Black cutworm <i>Agrotis ipsilon</i> (4th instar larvae) Silkworm <i>Bombyx mori</i> (5th instar larvae)	<i>H.bacteriophora</i> <i>S.carpocapsae</i>	Lab	100%	Zaki et al.,2000
Brinjal shoot and fruit borer, <i>Leucinodes orbonalis</i>	<i>S.carpocapsae</i> PDBC -11	Field		Ganga Visalakshy et al.,2009
	<i>Steinernema</i> sp. <i>H.indica</i>			Hussaini et al.,2002
<i>Spodoptera frugiperda</i> <i>Helicoverpa gelotopoeon</i>	<i>S.diaprepesi</i>	Lab		Milena et al.,2014
Fall armyworm <i>Spodoptera frugiperda</i> (1 st ,3 rd ,5 th instar,pupa)	<i>S. feltiae</i> All, Mexican (DD-136 x Breton) <i>S. bibionis.</i>	Lab	7%-20%	Fuxa et al.,1988
<i>Spodoptera litura</i> (pre pupa, pupa ,adult)	<i>S. feltiae</i>			Narayan & Gopalkrishna, 1987.
<i>S. litura</i>	<i>H. indica</i> <i>H. bacteriophora</i> <i>S. carpocapsae</i> , <i>S. longicaudum</i>	Lab		Acharya et al.,2020

<i>Spodoptera litura</i> <i>Galleria mellonella</i>	<i>S. feltiae</i> (DD-136) (=N. carpocapsae) <i>S. bibionis</i> <i>S. glaseri</i>	Lab		Kondo & Ishibashi , 1986;1986a;1987;1988
<i>Pectinophora gossypiella</i> (Late instars) <i>Heliothis virescens</i> <i>Trichoplusia ni</i> <i>Spodoptera exigua</i>	<i>S. riobrave</i> <i>S. carpocapsae</i> Kapow <i>H.bacteriophora</i> Cruiser	Lab		Gouge et al.,1996;1999
<i>Spodoptera litura</i>	<i>H.indica</i> <i>S.glaseri</i>	Glasshouse Microplot	50.6 %- 75.6 %	Umamaheswari et al. 2006.
<i>Spodoptera litura</i> (4 th instar larvae)	<i>S.carpocapsae</i>	Field	95%	Sezhian et al.,1996
<i>Spodoptera litura</i>	<i>H.indica</i>	Lab	50%	Dichusa et al.,2021
<i>H. armigera</i>	<i>S. glaseri</i>	Greenhouse		Patel & Vyas, 1995
<i>Spodoptera litura</i> (3 rd instar larvae)	<i>S.carpocapsae</i> <i>H.indica</i>			Raveendranath et al., 2007
Armyworm, <i>Spodoptera litura</i>	<i>S.pakistanense</i> <i>S. siamkayai</i> <i>S. ceratophorum</i> <i>S. bifurcatum</i> <i>H.indica</i>	Lab	74%- 95%	Javed et al.,2022
<i>Spodoptera littoralis</i> (3 rd instar larvae)	<i>H.bacteriophora</i> HP88 <i>S.glaseri</i> NJ <i>S.riobrave</i>	Lab	92%- 100%	Atwa & Hassan, 2014 Shairra & Nouh, 2014
Cotton leafworm, <i>Spodoptera littoralis</i>	<i>H.taysearae</i>	Lab	60%- 90%	Abd El Azim,2022
<i>S. littoralis</i> <i>Galleria mellonella</i>	<i>Heterorhabditis</i> sp. ELG <i>Heterorhabditis</i> sp. ELB <i>H. indica</i> , <i>H. egyptii</i> <i>S. riobrae</i> <i>S. carpocapsae</i>	Lab	61.4%- 100%	Abdel-Razek & Abdelgawad, 2007
<i>Spodoptera littoralis</i> (2 nd ,3 rd ,4 th ,5 th ,6 th instar larvae) <i>Plutella xylostella</i> (2 nd ,3 rd ,4 th instar larvae) <i>Pieris rapae</i> (2 nd ,5 th instar larvae)	<i>S. carpocapsae</i> All <i>S. caprocapsae</i> S2 <i>H. indicus</i> SAA2 <i>H. bacteriophora</i> HP88	Lab		Salem et al.,2007
Cabbage worm	<i>H.tayserae</i>	Lab	55-	Saleh, 1995

<i>Pieris rapae</i>			100%	
Cabbage butterfly, <i>Pieris brassicae</i>	<i>H. pakistanensis</i>	Field	61.16%	Askary & Ahmad, 2020
	<i>S. feltiae</i> HR1 <i>H.bacteriophora</i> HR2	Lab	12% - 72.08%	Kasi et al.,2021
<i>Spodoptera littoralis</i> <i>Agrotis ipsilon</i>	<i>H.bacteriophora</i> BA1 <i>S.carpocapsae</i> BA2	Lab Field	100%	Saleh &Ragab , 1999; Saleh et al.,2015.
<i>Spodoptera littoralis</i> <i>Agrotis ipsilon</i>	<i>S.monticolum</i> <i>H.bacteriophora</i>	Lab	97.77%-100%	Sobhy et al.,2020
Black cutworm <i>Agrotis ipsilon</i>	<i>Steinernema feltiae</i> (= <i>Neoaplectana carpocapsae</i>) Mexican Kapow, <i>S. bibionis</i> , <i>H.heliothidis</i> .	Field	50% reduction in plant damage	Capinera et al.,1988
Turnip moth <i>Agrotis segetum</i>	<i>S.carpocapsae</i>	Lab		Ebrahimi et al.,2019
<i>Agrotis ipsilon</i> <i>Galleria mellonella</i> .	<i>S.carpocapsae</i> HB310	Lab	90.48% 82.33%	NanGong et al.,2021
Cotton leafworm, <i>Spodoptera littoralis</i> Black cutworm, <i>Agrotis ipsilon</i>	<i>Heterorhabditis</i> sp. TAN5	Lab	24 %-100% 18%-96%	Nouh, 2021
Black cutworm <i>Agrotis ipsilon</i>	<i>S.carpocapsae</i>	Field		Levine & Oloumi-Sadeghi,1993
Tobacco cutworm, <i>Spodoptera litura</i>	<i>S. carpocapsae</i> PC <i>H. bacteriophora</i> HY <i>S. monticola</i> CR	Lab	100%	Park et al.,2001
<i>Spodoptera litura</i>	<i>H.bacteriophora</i>	Lab		Baweja & Sehgal, 1997
<i>Spodoptera litura</i> <i>Spodoptera frugiperda</i>	<i>H. indica</i> <i>S. carpocapsae</i>	Lab		Acharya et al.,2020; 2020a
<i>Spodoptera frugiperda</i> <i>Heliothis zea</i>	<i>S. feltiae</i>			Richter and Fuxa, 1990
Indianmeal moth <i>Plodia interpunctella</i>	<i>H.bacteriophora</i> HP88,Lewiston,Oswego <i>H.indica</i> Homl <i>H.marelatus</i> Point Reyes <i>H.megidis</i> UK211 <i>H.zealandica</i> NZH3	Lab	44%	Mbata & Shapiro-Ilan,2005
European corn borer, <i>Ostrinia nubilalis</i>	<i>N.carpocapsae</i> DD-136	Lab Field		Lewis &Raun,1978
Corn earworm <i>Helicoverpa zea</i> Fall armyworm	<i>S. sp.</i>	Field	49.4 - 46.1% parasitiz	Raulston et al.,1992

<i>Spodoptera fragiperda</i> (prepupae and pupae)			ation	
Fall armyworm <i>Spodoptera frugiperda</i>	<i>S.carpocapsae</i>		28%	Espky & Capinera,1993;1994
<i>Spodoptera frugiperda</i>	<i>S.arenarium</i> All <i>Heterorhabditis</i> sp., RSC02 <i>S.sp.</i> IBCP-n6 <i>H.indica</i>	Lab, Greenh ouse, Field	77.5 and 87.5%	Garcia et al.,2008; Andalo et al.2010
Fall armyworm (FAW), <i>Spodoptera frugiperda</i> (2nd and 5th larval instars)	<i>H. indica</i> AUT 13.2 , <i>S.siamkayai</i> APL 12.3	Lab , Greenh ouse,fi eld	33%- 83%	Wattanachaiyingcharoen, 2021
Fall armyworm <i>Spodoptera frugiperda</i>	<i>S.carpocapsae</i>	Lab	35%	Viteri et al.,2018
<i>S. frugiperda</i>	<i>H. indica</i> , <i>S.carpocapsae</i> <i>S. glaseri</i>	Field		Negrisola et al.,2010
<i>Spodoptera frugiperda</i> <i>Helicoverpa gelotopoeon</i>	<i>S. diaprepesi</i>	Lab		Caccia et al.,2014
Cotton bollworm <i>Helicoverpa armigera</i>	<i>S. feltiae</i>	Lab, Glassho use	75%- 90%	Glazer & Navon, 1990; Glazer 1997;Navon et al.,2002; Shahina et al.2014; Ebrahimi et al.,2018
Corn earworm, <i>Helicoverpa (=Heliothis) zea</i>	<i>S.riobravus</i> <i>S.carpocapsae</i>	Field	90%	Cabanillas & Raulston, 1994; 1995; 1996;1996a;1996
Corn earworm, <i>Heliothis zea</i>	<i>N.carpocapsae</i> DD-136	Field	58%- 88%	Bong & Sikorowski, 1983; Bong 1986
Pink bollworm <i>Pectinophora gossypiella</i>	<i>S.carpocapsae</i>			Lindegren et al., 1993
	<i>S.riobrave</i> <i>H.bacteriophora</i> HP88	Lab	76.43%- 86.45%	Shairra & Nouh, 2014; Shairra et al.,2016
Pink bollworm, <i>Pectinophora gossypiella</i> Cabbage looper <i>Trichoplusia ni</i> Beet army worm <i>Spodoptera exigua</i>	<i>S.carpocapsae</i> <i>S. riobravus</i>	Lab Field	92.5% - 100%	Henneberry <i>et al.</i> , 1995;1995a;1996;1996a
Pink bollworm,	<i>S.riobravus</i>	Field	25.7-	Jech & Henneberry,

<i>Pectinophora gossypiella</i>			92.4%	1997
Codling moth <i>Cydia pomonella</i> (diapausing larvae)	<i>S. carpocapsae</i> Sal <i>S. feltiae</i> Umea <i>S. riobrave</i> <i>H. zealandica</i> <i>H. bacteriophora</i>	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 (<i>Cydia pomonella</i>)	<i>S.feltiae</i> <i>S.carpocapsae</i> <i>S.yirgalemense</i> <i>H. zealandica</i> <i>H.pakistanensis</i> NBAIR H-05	Field	43.85 - 86.27 %	Sledzevskaya, 1987; Cossentine et al., 2002; 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
	<i>S. carpocapsae</i> Bakişli <i>S. feltiae</i> ES-3 <i>H.bacteriophora</i> TOK20 <i>H. bacteriophora</i> 11-KG	Lab	71.5%- 82.63%	Yagci et al.,2021
Filbertworm, <i>Cydia latiferreana</i>	<i>S. carpocapsae</i>	Lab,Fie ld	65%- 92%	Chambers et al.,2010
Carob moth <i>Ectomyelois ceratoniae</i>	<i>S.carpocapsae</i> <i>S. feltiae</i>	Lab	76.5% 79.75%	Memari et al.,2016
Diamond backmoth <i>Plutella xylostella</i>	<i>S.carpocapsae</i> All <i>S.riobravus</i>	Lab , greenho use, Field	79.1%	Baur et al.,1997; 1998; Shinde &Singh, 2000; Singh&Shinde, 2002
	<i>S.carpocapsae</i>	Lab		Ratnasinghe &Hague, 1997; Schroer & Ehlers , 2005; Schroer et al.,2005

	<i>H.indica</i> <i>S.karii</i> <i>S.wesieri</i>	Lab	86.7%- 96.0%	Nyasani et al., 2008; 2008a
	<i>S.carpocapsae</i> <i>H. bacteriophora</i>	Lab	72.6%– 96%	Zolfagharian et al., 2016
	<i>H. bacteriophora</i> BA1 <i>S.carpocapsae</i> BA2	Greenh ouse	64.4%- 79.8%	Hussein et al.,2015
Potato tuber moth, <i>Phthorimaea</i> <i>operculella</i> (second ,fourth instar larvae , prepupa)	<i>S.carpocapsae</i> <i>S. feltiae</i> <i>S. glaseri</i> <i>S. bibionis</i> <i>H. bacteriophora</i>	Lab		Ivanova et al.,1994; Hassani-Kakhki et al., 2013.
Potato tuber moth, <i>Phthorimaea</i> <i>operculella</i>	<i>S.carpocapsae</i> , <i>S. feltiae</i> , <i>H. bacteriophora</i>	Lab	40%- 100%	Lacey & Kroschel, 2009; Kepenekci et al., 2013
Squash vine borer <i>Melittia cucurbitae</i>	<i>Steinernema riobrave</i> TX <i>S. feltiae</i> SN <i>S.carpocapsae</i> All <i>S. carpocapsae</i> Sal <i>H.bacteriophora</i> Hb <i>H. sp.</i> Hbl	Field	19%- 61%	Canhila &Carner, 2006
Red hairy caterpillar, <i>Amsacta albistriga</i>	<i>Steinernema</i> sp. <i>H. indica</i>	Lab Micropl ot	80% 42%	Prabhu & Sudheer, 2008
False codling moth (FCM), <i>Thaumatotibia</i> <i>leucotreta</i>	<i>S. yirgalemense</i> <i>S.khoisanane</i> <i>H. zealandica</i> <i>H. bacteriophora</i>	Lab Field		Manrakhan et al.,2013; Malan & Moore, 2016; Malan et al.,2011;2018
False codling moth (FCM), <i>Thaumatotibia</i> <i>leucotreta</i>	<i>S. yirgalemense</i> <i>H. zealandica</i> <i>S.litchii</i>	Lab	93.5%- 100%	Steyn et al.,2017
<i>Dalaca pallens</i>	<i>S. australe</i> QU N3 <i>S.unicornum</i> QU N13	Lab	95%- 100%	Maldonado et al., 2012
Sugarcane early shoot borer, <i>Chilo infuscatellus</i>	<i>H.indica</i> LN2 <i>H. bacteriophora</i> LN8 <i>Heterorhabditis</i> sp. HII <i>S.carpocapsae</i> <i>S. glaseri</i> <i>S. riobrave</i> <i>S. feltiae</i>	Lab		Sankaranarayanan et al., 2011
<i>Earias insulana</i> <i>Heliothis armigera</i>	<i>S.carpocapsae</i> Mexican	Field	85%- 95%	Glazer & Navon, 1989;1990

<i>Spodoptera littoralis</i>				Glazer et al., 1991; 1992
Mexican rice borer <i>Eoreuma loftini</i>	<i>S. riobravus</i>	Lab Field	100%	Legaspi et al.,2000
Brazilian apple leafroller <i>Bonagota Salubricola</i>	<i>H. bacteriophora</i> RS107 <i>H. bacteriophora</i> RS57	Lab Field	61.1%- 70.2%	Negrisoni et al.,2010
<i>Mocis latipes</i>	<i>H. bacteriophora</i>			Gonzalez-Ramirez et al.,2000
<i>Ostrinia furnacalis</i> <i>H. armigera</i> <i>S. litura</i>	<i>S.abbasi</i> MBLB <i>S minutum</i> <i>S. tami</i> <i>H. indica</i> PBCB	Lab	28.15%- 100%	Caoili et al.,2018
wax moth, <i>Galleria mellonella</i> , yellow meal worm, <i>Tenebrio molitor</i> , beet armyworm, <i>Spodoptera exigua</i> , black cutworm, <i>Agrotis ipsilon</i> , European corn borer, <i>Ostrinia nubilalis</i>	<i>S. carpocapsae</i> <i>S. glaseri</i> <i>S. feltiae</i> <i>S. riobravus</i> <i>H.bacteriophora</i>	Lab		Caroli et al.,1996
<i>Spodoptera exigua</i> <i>Pseudaletia unipuncta</i>	<i>S. feltiae</i>	Lab	68%- 100%	Kaya, 1985
<i>Spodoptera exigua</i> (prepupae , pupae , adults)	<i>N.carpocapsae</i>	Lab		Kaya & Grieve,1982
Stem borer of maize <i>Sesamia calamistis</i>	<i>H. sp.</i>	Lab	4-57%	Claudius-Cole, 2018
Fall armyworm <i>Spodoptera frugiperda</i> greater wax moth <i>Galleria mellonella</i> black cutworm <i>Agrotis ipsilon</i>	<i>S. carpocapsae</i> All Mexican	Lab	1%-28%	Espky & Capinera, 1994
<i>Pseudaletia unipuncta</i>	<i>H.bacteriophora</i> <i>S. carpocapsae</i> <i>S. glaseri</i>	Lab		Rosa et al.,2002
Rice leaf folder, <i>Cnaphalocrosis</i> <i>medinalis</i>	<i>N. carpocapsae</i> DD-136	Lab		Srinivas & Prasad, 1991
Ghost moth <i>Hepialus californicus</i>	<i>H.hepialus</i>		72%	Strong et al.,1996
Navel orange worm <i>Amyelois transitella</i>	<i>S. carpocapsae</i> <i>S. feltiae</i>	Field	72%	Siegel et al.,2004

European corn borer, <i>Ostrinia nubilalis</i>	<i>N. carpocapsae</i> DD-136	Lab, Field		Lewis & Raun, 1978
Melonworm, <i>Diaphania hyalinata</i>	<i>S. carpocapsae</i>			Shannag & Capinera, 1995

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UNDER PEER REVIEW