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, lepidoptearan 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).

Bioefficay 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 brightners (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/m^2) 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 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*) 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.riobrave* 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.,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).

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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 Lha^{-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 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 (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 (*Galleria mellonella*)	*Heterorhabditis bacteriophora* *Steinernema glaseri* *S. scarabaei* *S. feltiae*	Lab		Hyrsl,2011; Rahoo et al.,2018
	H.megidis *S.carpocapsae*	Lab		Saunders & Webster, 1999
	H. heliothidis *S.glaseri*	Lab		Zervos et al.,1991
	S. surkhetense	Lab		Trinh et al.,2021
	S. feltiae DDKB-17 *H. bacteriophora* AVB-15	Lab	87%-100%	Yuksel & Canhilal, 2019
	H.indica	Lab		Khashaba et al.,2020
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* *S. feltiae* *H.indicus*	Lab		Karunakar et al.,1999
Spodoptera litura,	*S.siamkayai*	Lab		Adiroubane et al.,

Plutella xylostella, *Leucinodes orbonalis*, *Earais vitella*, *Cnaphalocrocis medinalis*.				2010
Galleria mellonella *Spodoptera litura*	*S.carpocapsae*	Lab		Fuchi et al.,2016
Spodoptera exigua *Harrisinia brillians* pupae	*N.carpocapsae*	Lab	63% 55%	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	75.7%-100%	Belair et al.,2003
Tomato leafminer (*Tuta absoluta*)	*S.carpocapsae* All	Lab, greenhouse	Percent of mine reduction 12.9%.	Sabry et al.,2016
	S.carpocapsae *S. feltiae* *H.bacteriophora*		88.6 % 92.0% 76.3%	Van Damme et al., 2016
	S. feltiae	Field		Williams &Walters, 1999
	Heterorhabdities sp. *S. karii*	Lab		Mutegi et al.,2017
	S. yirgalemense 157-C *S.jeffreyense*	Lab	58.8% 46.4%	Dlamini et al.,2020
	S.carpocapsae, B14 *S. feltiae* Bpa *H.bacteriophora* DG46	Lab , greenhouse	77.1%-91.7%	Batalla-Carrera et al., 2010
	S.affine 46 *S. carpocapsae* 1133,	Field	39.3%-90.7 %	Gozel & Kasap ,2015

	S. feltiae 879 *H. bacteriophora* 1144			
Stem borer (*Sesamia calamistis*)	*H.bacteriophora* *S. feltiae*	Lab	4%- 57%	Claudius-Cole,2018
Turnip moth (*Agrotis segetum*) (L3,L5)	*H.indica* *H.bacteriophora*	Lab	93.33% 81.67%	Vashisth et al.,2018
Red-backed cutworm (*Euxoa ochrogaster*) Army cutworm (*Euxoa* auxiliaries) pale western cutworm (*Agrotis orthogonia*) Black army cutworm (*Actebia fennica*) Bertha armyworm (*Mamestra configurata*)	*S. feltiae* *H.bacteriophora*	Lab		Morris, 1985
Agrotis ipsilon *A. segtetum*	S *bicormutum* PDBC 2.1, 3.1, 3.2 S.*carpocapsae* PDBC 6.11, 6.61,13.1 *H indica* PDBC 6.71, 13.3	Lab	100%	Hussaini et al.,2000
Agrotis ipsilon	*S.riobrave* *S.carpocapsae* E 76-S *H.bacteriophora* FLH-4-H *H.indica*216-H *H.bacteriophora* HP88	Field Lab	Reduction 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 (*Peridroma saucia*)	*S.carpocapsae* *S.feltiae* *H.bacteriophora* *H.indica*	Lab	33%- 70%	Yuksel et al.,2018
Oriental fruit moth (*Grapholita molesta*)	*S.rarum* RS69 *H.bacteriophora* RS33	Lab, field	94% - 97.0%	Negrisoli et al.,2013
Peachtree borer, (*Synanthedon exitiosa*) (*S.pictipes*)	*H.heliothidis* *S.carpocapsae* *H. bacteriophora*	Field	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.*	Field	90%	Deseo & Miller, 1985; Kaya

tipuliformis)				&Brown, 1986; Miller & Bedding, 1982; Miller,1989; Begley, 1990; Nachtigall & Dickler, 1992
Grape root borer (*Vitacea polistiformis*)		Lab Greenhouse		Williams et al.,2002
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		Sharmila et al.,2018
S. litura (3rd, 4th , 5th instar larvae)	*H.indica*	Lab	82.73%	Kamaliya et al.,2019
	H. indica PBCB	Lab	88.67%	Caoili et al., 2018
	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

orbonalis)	*Steinernema* sp. *H.indica*			Hussaini et al.,2002
Spodoptera frugiperda , *Helicoverpa gelotopoeon*	*S.diaprepesi*	Lab		Milena et al.,2014
Fall armyworm *(Spodoptera frugiperda*) (1^{st},3^{rd},5^{th} 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* *H. bacteriophora* *S. carpocapsae,* *S. longicaudum*	Lab		Acharya et al.,2020
Spodoptera litura, *Galleria mellonella*	*S. feltiae* (DD-136) (=N. carpocapsae) *S. bibionis* *S. glaseri*	Lab		Kondo & Ishibashi , 1986;1986a;1987;1988
Pectinophora gossypiella (Late instars), *Heliothis virescens* , *Trichoplusia ni* , *Spodoptera exigua*	*S. riobrave* *S. carpocapsae* Kapow *H.bacteriophora* Cruiser	Lab		Gouge et al.,1996;1999
Spodoptera litura	*H.indica* *S.glaseri*	Glasshouse Microplot	50.6 %- 75.6 %	Umamaheswari et al. 2006.
Spodoptera litura (4^{th} 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 (3^{rd} instar larvae)	*S.carpocapsae* *H.indica*			Raveendranath et al., 2007
Armyworm, (*Spodoptera litura*)	*S.pakistanense* *S. siamkayai* *S. ceratophorum* *S. bifurcatum* *H.indica*	Lab	74%- 95%	Javed et al.,2022
Spodoptera littoralis (3^{rd} instar larvae)	*H.bacteriophora* HP88 *S.glaseri* NJ	Lab	92%- 100%	Atwa & Hassan, 2014

	S.riobrave			Shairra & Nouh, 2014
Cotton leafworm, (*Spodoptera littoralis*)	*H.taysearae*	Lab	60%-90%	Abd El Azim,2022
S. littoralis *G. mellonella*	*Heterorhabditis* sp. ELG *Heterorhabditis* sp. ELB *H. indica,* *H. egyptii* *S. riobravae* *S. carpocapsae*	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. carpocapase* All *S. caprocapsae* S2 *H. indicus* SAA2 *H. bacteriophora* HP88	Lab		Salem et al.,2007
Cabbage worm (*Pieris rapae*)	*H.tayserae*	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 ipsilon*	*H.bacteriophora* BA1 *S.carpocapsae* BA2	Lab Field	100%	Saleh &Ragab , 1999; Saleh et al.,2015.
Spodoptera littoralis, *Agrotis ipsilon*	*S.monticolum* *H.bacteriophora*	Lab	97.77%-100%	Sobhy et al.,2020
Black cutworm (*Agrotis ipsilon*)	*Steinernema feltiae* (= *Neoaplectana carpocapsae*) Mexican Kapow, *S. bibionis,* *H.heliothidis.*	Field	50% reduction in plant damage	Capinera et al.,1988
Turnip moth (*Agrotis segetum*)	*S.carpocapsae*	Lab		Ebrahimi et al.,2019
Agrotis ipsilon *Galleria mellonella.*	*S.carpocapsae* HB310	Lab	90.48% 82.33%	NanGong et al.,2021
Cotton leafworm, (*Spodoptera littoralis*) Black cutworm, (*Agrotis ipsilon*)	*Heterorhabditis* sp. TAN5	Lab	24 %-100% 18%-96%	Nouh, 2021

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*			Richter and Fuxa, 1990
Indianmeal moth (*Plodia interpunctella*)	*H.bacteriophora* HP88,Lewiston,Oswego *H.indica* Homl *H.marelatus* Point Reyes *H.megidis* UK211 *H.zealandica* 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 fragiperda*) (prepupae and pupae)	*S.* sp.	Field	49.4 - 46.1% parasitization	Raulston et al.,1992
Fall armyworm (*Spodoptera frugiperda*)	*S.carpocapsae*		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%	Wattanachaiyingcharoen, 2021
Fall armyworm (*Spodoptera frugiperda*)	*S.carpocapsae*	Lab	35%	Viteri et al.,2018
S. frugiperda	*H. indica*, *S.carpocapsae* *S. glaseri*	Field		Negrisoli et al.,2010

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) zea*	*S.riobravis* *S.carpocapsae*	Field	90%	Cabanillas & Raulston, 1994; 1995; 1996;1996a;1996
Corn earworm, (*Heliothis zea*)	*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* *H. zealandica* *H.bacteriophora*	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;

	H. zealandica *H.pakistanensis* NBAIR H-05	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 *S. feltiae* ES-3 *H.bacteriophora* TOK20 *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 *S.karii* *S.wesieri*	Lab	86.7%-96.0%	Nyasani et al., 2008; 2008a
	S.carpocapsae *H. bacteriophora*	Lab	72.6%–96%	Zolfagharian et al., 2016
	H. bacteriophora BA1 *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.

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 (FCM), (*Thaumatotibia Leucotreta*)	*S. yirgalemense* *S.khoisanae* *H. zealandica* *H. bacteriophora*	Lab Field		Manrakhan et al.,2013; Malan & Moore, 2016; Malan et al.,2011;2018
False codling moth (*Thaumatotibia Leucotreta*)	*S. yirgalemense* *H. zealandica* *S.litchii*	Lab	93.5%-100%	Steyn et al.,2017
Dalaca pallens	*S. australe* QU N3 *S.unicornum* QU N13	Lab	95%-100%	Maldonado et al., 2012
Sugarcane early shoot borer, (*Chilo infuscatellus*)	*H.indica* LN2 *H. bacteriophora* LN8 *Heterorhabditis* sp. HII *S.carpocapsae* *S. glaseri* *S. riobrave* *S. feltiae*	Lab		Sankaranarayanan et al., 2011
Earias insulana *Heliothis armigera* *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. armigera* *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

yellow meal worm, (*Tenebrio molitor*) beet armyworm, (*Spodoptera exigua),* black cutworm, (*Agrotis ipsilon*), European corn borer, (*Ostrinia nubilalis*)	*S. feltiae* *S. riobravis* *H.bacteriophora*			
Spodoptera exigua Pseudaletia unipuncta	*S. feltiae*	Lab	68%-100%	Kaya, 1985
Spodoptera exigua (prepupae , pupae , adults)	*N.carpocapsae*	Lab		Kaya & Grieve,1982
Stem borer of maize (*Sesamia calamistis*)	*H.* sp.	Lab	4-57%	Claudius-Cole, 2018
Fall armyworm (*Spodoptera frugiperda*), greater wax moth (*Galleria mellonella*), black cutworm (*Agrotis ipsilon*)	*S. carpocapsae* All Mexican	Lab	1%-28%	Espky & Capinera, 1994
Pseudaletia unipuncta	*H.bacteriophora* *S. carpocapsae* *S. glaseri*	Lab		Rosa et al.,2002
Rice leaf folder, (*Cnaphalocrosis medinalis*)	*N. carpocapsae* DD-136	Lab		Srinivas & Prasad, 1991
Ghost moth (*Hepialus californicus*)	*H.hepialus*		72%	Strong et al.,1996
Navel orange worm (*Amyelois transitella*)	*S. carpocapsae* *S. feltiae*	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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