International Journal of Plant & Soil Science

34(14): 19-47, 2022; Article no.IJPSS.85833
ISSN: 2320-7035

Management of Lepidopteran Insect Pests through Entomopathogenic Nematodes: An Overview

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/IJPSS/2022/v34i1430988

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/85833

Review Article

Received 02 February 2022
Accepted 10 April 2022
Published 15 April 2022

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.

Keywords: Entomopathogenic nematodes(EPNs), biocontrol agent, lepidoptearan insect, Steinernema spp., Heterorhabditis spp.

1. 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" [1,2]. "The female may produce eggs as high as 30,000 eggs per day which may create substantial problems for agricultural crops" [3]. 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

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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 [4,5]. EPNs have many positive characteristics like wide host range, host searching ability, short life cycles, easy mass culture and application, and good persistence etc. [6-10].

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 [11], but it is used as a standard host for observations on virulence of many biological control agents like EPNs [12-14].

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" [15,16].

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 [17,18] and optical brightners [19].

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., [20] "reported the FAW's susceptibility to EPNs. Acharya et al*.,* [21] 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 [22] 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 [22] 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 [23-25].Spraying of IJs at dusk is reported to reduce the negative effects of sunlight by maintaining high RH" [26].

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 [27], the diapausing larvae in soil during the winter are susceptible [28]. Due to lower temperature during winter, *H.bacteriophora* has been found to be more effective than *S.riobrave* for the control of pink bollworm [28].

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. [29], "and Unruh and Lacey [30] 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) [31,32]. "Used under optimal conditions of warm temperatures and available free water, EPNs can be effective control agents of cocooned CM larvae in orchards [29,30,33-35] and fruit bins [36-38]. Navaneethan et al., [39] reported that efficacy of *S.feltiae* against the diapausing CM larvae by using a surfactant-polymer formulation.

2. 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 [40]. EPNs can effectively control several lepidopteran species [40, 41, 42, Negrisoli et al., [43] but matching the most suitable nematode with the target host is a critical component for success in any biocontrol programme [44].

"Factors such as temperature and sunlight are reported to affect the activity of IJs [23-25]. Spraying of IJs at dusk is reported to reduce the negative effects of sunlight by maintaining high RH [26]. The use of local isolates, which are adapted to local temperatures, was reported to give a high level of efficacy against the target pest" [18].

"Timing of application of entomopathogenic nematodes with the life cycle of the target insect is a key factor to increase efficacy [45]. Pre and post application irrigation is essential for nematode movement, persistence, and infection" [32]."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. [46] "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" [47]. Entomopathogenic nematodes can be applied with equipment developed for pesticides, including backpack, boom (with or without air assistance), aerial, and electrostatic sprayers [5].

Entomopathogenic nematodes have been used with variable success against lepidopteran pests, including those found in the soil, in cryptic habitats, on foliage [42]. 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" [203,204]. "*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 [205]."

"The stage of insect development has a significant effect on vulnerability to EPNs [206,60,40]. *Spodoptera exigua* (Hubner), prepupa was the most susceptible stage, showing the highest mortality

Table 1. Bioefficacy of entomopathogenic nematodes against lepidopteran insect pests

Pest	Nematode	Laboratory /field experiment	Efficacy	Reference
Wax moth (*Galleria mellonella*)	*Heterorhabditis bacteriophora*	Lab		Hyrsl,[48]
	Steinernema glaseri *S. scarabaei* *S. feltiae*			Rahoo et al.,[49]
	H.megidis *S.carpocapsae*	Lab		Saunders & Webster, [50]
	H. heliothidis *S.glaseri*	Lab		Zervos et al.,[51]
	S. surkhetense	Lab		Trinh et al., [52]
	S. feltiae DDKB-17 *H. bacteriophora* AVB-15	Lab	87%-100%	Yuksel & Canhilal, [53]
	H.indica	Lab		Khashaba et al.,[54]
Galleria mellonella, Helicoverpa armigera Spodoptera litura	*S.abbasi* CS38	Lab	100%	Heena et al., [55]
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., [56]
Spodoptera litura, Plutella xylostella, *Leucinodes orbonalis*, *Earais vitella, Cnaphalocrocis medinalis.*	*S.siamkayai*	Lab		Adiroubane et al., [57]

Pest	Nematode	Laboratory /field experiment	Efficacy	Reference
Galleria mellonella *Spodoptera litura*	*S.carpocapsae*	Lab		Fuchi et al.,[58]
Spodoptera exigua *Harrisinia brillians* pupae	*N.carpocapsae*	Lab	63% 55%	Kaya & Hara, [59,60]
Wax moth (*Galleria mellonella*), Pink bollworm (*Pectinophora gossypiella*), Eggplant fruit borer (*Leucinodes orbonalis*) Armyworm (*Spodoptera litura*)	*S.kraussei*	Lab		Khan et al., [61]
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., [62]
Tomato leafminer (*Tuta absoluta*)	*S.carpocapsae* All	Lab, greenhouse	Percent of mine reduction 12.9%.	Sabry et al., [63]
	S.carpocapsae *S. feltiae* *H.bacteriophora*		88.6 % 92.0% 76.3%	Van Damme et al., [64]
	S. feltiae	Field		Williams &Walters, [65]
	Heterorhabdities sp. *S. karii*	Lab		Mutegi et al., [66]
	S. yirgalemense 157-C *S.jeffreyense*	Lab	58.8% 46.4%	Dlamini et al., [67]
	S.carpocapsae, B14	Lab , greenhouse	77.1%-	Batalla-Carrera et al., [42]

Pest	Nematode	Laboratory /field experiment	Efficacy	Reference
	S. feltiae Bpa *H.bacteriophora* DG46 *S.affine* 46 *S. carpocapsae* 1133, *S. feltiae* 879 *H. bacteriophora* 1144	Field	91.7% 39.3%- 90.7 %	Gozel & Kasap [68]
Stem borer (*Sesamia calamistis*)	*H.bacteriophora* *S. feltiae*	Lab	4%- 57%	Claudius-Cole, [69]
Turnip moth (*Agrotis segetum*) (L3,L5)	*H.indica* *H.bacteriophora*	Lab	93.33% 81.67%	Vashisth et al., [70]
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, [71]
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., [72]
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., [73] Yuksel & Canhilal, [53,74] Hassan et al., [75]; Shairra et al.,[76]
Variegated cutworm	*S.carpocapsae*	Lab	33%-70%	Yuksel et al., [74]

Pest	Nematode	Laboratory /field experiment	Efficacy	Reference
(*Peridroma saucia*)	*S.feltiae* *H.bacteriophora* *H.indica*			
Oriental fruit moth (*Grapholita molesta*)	*S.rarum* RS69 *H.bacteriophora* RS33	Lab, field	94% -97.0%	Negrisoli et al., [77]
Peachtree borer, (*Synanthedon exitiosa*) (*S.pictipes*)	*H.heliothidis* *S.carpocapsae* *H. bacteriophora*	Field	80%	Cossentine et al.,[78]; Cottrell &Shapiro-Ilan, [79];Shapiro-Ilan et al.,[80-84]
Currant borer moth, (*Synanthedon tipuliformis*)	*N.bibionis* *Steinernema sp.*	Field	90%	Deseo & Miller, [85] Kaya &Brown, [86] Miller & Bedding, [87] Miller,[88]; Begley, [31]; Nachtigall & Dickler, [34]
Grape root borer (*Vitacea polistiformis*)		Lab Greenhouse		Williams et al., [89]
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., [90]
S. litura (3rd, 4th , 5th instar larvae)	*H.indica*	Lab	82.73%	Kamaliya et al., [91]
	H. indica PBCB	Lab	88.67%	Caoili et al., [92]
	Steinernema sp. 64-2 *S. carpocapsae* A24	Lab	100%	Yan et al., [93]

Pest	Nematode	Laboratory /field experiment	Efficacy	Reference
	S. carpocapsae All *S. carpocapsae* G-R3a-2 *S. longicaudum* X-7 *H. indica* 212-2			
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., [94]
Brinjal shoot and fruit borer, (*Leucinodes orbonalis*)	*S.carpocapsae* PDBC -11 *Steinernema* sp. *H.indica*	Field		Ganga Visalakshy et al., [95] Hussaini et al., [96]
Spodoptera frugiperda , *Helicoverpa gelotopoeon*	*S.diaprepesi*	Lab		Milena et al., [97]
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.,[98]
Spodoptera litura (pre pupa, pupa ,adult)	*S. feltiae*			Narayan & Gopalkrishna, [99]
S. litura	*H. indica* *H. bacteriophora* *S. carpocapsae*, *S. longicaudum*	Lab		Acharya et al., [21]
Spodoptera litura, Galleria mellonella	*S. feltiae* (DD-136) (=N. carpocapsae) *S. bibionis* *S. glaseri*	Lab		Kondo & Ishibashi, [100-103]

Pest	Nematode	Laboratory /field experiment	Efficacy	Reference
Pectinophora gossypiella (Late instars), *Heliothis virescens* , *Trichoplusia ni* , *Spodoptera exigua*	*S. riobrave* *S. carpocapsae* Kapow *H.bacteriophora* Cruiser	Lab		Gouge et al., [23,104]
Spodoptera litura	*H.indica* *S.glaseri*	Glasshouse Microplot	50.6 %-75.6 %	Umamaheswari et al. [105].
Spodoptera litura (4th instar larvae)	*S.carpocapsae*	Field	95%	Sezhian et al., [106]
Spodoptera litura	*H.indica*	Lab	50%	Dichusa et al., [107]
H. armigera	*S. glaseri*	Greenhouse		Patel & Vyas, [108]
Spodoptera litura (3rd instar larvae)	*S.carpocapsae* *H.indica*			Raveendranath et al., [109]
Armyworm, (*Spodoptera litura*)	*S.pakistanense* *S. siamkayai* *S. ceratophorum* *S. bifurcatum* *H.indica*	Lab	74%-95%	Javed et al., [110]
Spodoptera littoralis (3rd instar larvae)	*H.bacteriophora* HP88 *S.glaseri* NJ *S.riobrave*	Lab	92%-100%	Atwa & Hassan, [111] Shairra & Nouh, [112]
Cotton leafworm, (*Spodoptera littoralis*)	*H.taysearae*	Lab	60%-90%	Abd El Azim, [113]
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, [114]
Spodoptera littoralis (2nd,3rd,4th,5th,6th instar larvae) ,	*S. carpocapase* All *S. caprocapsae* S2 *H. indicus* SAA2	Lab		Salem et al., [115]

Pest	**Nematode**	**Laboratory /field experiment**	**Efficacy**	**Reference**
Plutella xylostella (2nd,3rd,4th instar larvae), *Pieris rapae* (2nd ,5th instar larvae)	*H. bacteriophora* HP88			
Cabbage worm (*Pieris rapae*)	*H.tayserae*	Lab	55-100%	Saleh, [116]
Cabbage butterfly, (*Pieris brassicae*)	*H. pakistanensis* *S. feltiae* HR1 *H.bacteriophora* HR2	Field Lab	61.16% 12% -72.08%	Askary & Ahmad, [117] Kasi et al.,[118]
Spodoptera littoralis, Agrotis ipsilon	*H.bacteriophora* BA1 *S.carpocapsae* BA2	Lab Field	100%	Saleh &Ragab , [119]; Saleh et al., [120]
Spodoptera littoralis, Agrotis ipsilon	*S.monticolum H.bacteriophora*	Lab	97.77%-100%	Sobhy et al., [121]
Black cutworm (*Agrotis ipsilon*)	*Steinernema feltiae* (= *Neoaplectana carpocapsae*) Mexican Kapow, *S. bibionis*, *H.heliothidis*.	Field	50% reduction in plant damage	Capinera et al.,[122]
Turnip moth (*Agrotis segetum*)	*S.carpocapsae*	Lab		Ebrahimi et al., [123]
Agrotis ipsilon Galleria mellonella.	*S.carpocapsae* HB310	Lab	90.48% 82.33%	NanGong et al., [124]
Cotton leafworm, (*Spodoptera littoralis*) Black cutworm, (*Agrotis ipsilon*)	*Heterorhabditis* sp. TAN5	Lab	24 %- 100% 18%- 96%	Nouh, [125]
Black cutworm (*Agrotis ipsilon*)	*S.carpocapsae*	Field		Levine & Oloumi-Sadeghi,[126]
Tobacco cutworm, (*Spodoptera litura*)	*S. carpocapsae* PC *H. bacteriophora* HY *S. monticola* CR	Lab	100%	Park et al., [127]
Spodoptera litura	*H.bacteriophora*	Lab		Baweja & Sehgal, [128]

Pest	**Nematode**	**Laboratory /field experiment**	**Efficacy**	**Reference**
Spodoptera litura, *Spodoptera frugiperda*	*H. indica* *S. carpocapsae*	Lab		Acharya et al.,[21,129]
Spodoptera frugiperda , *Heliothis zea*	*S. feltiae*			Richter and Fuxa, [130]
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, [131]
European corn borer, (*Ostrinia nubilalis*)	*N.carpocapsae* DD-136	Lab Field		Lewis &Raun, [132]
Corn earworm (*Helicoverpa zea*), Fall armyworm (*Spodoptera fragiperda*) (prepupae and pupae)	*S.* sp.	Field	49.4 -46.1% parasitization	Raulston et al., [133]
Fall armyworm (*Spodoptera frugiperda*)	*S.carpocapsae*		28%	Espky & Capinera,[134,135]
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.,[47]; Andalo et al. [136]
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, [137]
Fall armyworm (*Spodoptera frugiperda*)	*S.carpocapsae*	Lab	35%	Viteri et al., [138]
S. frugiperda	*H. indica*, *S.carpocapsae* *S. glaseri*	Field		Negrisoli et al.,[139]

Pest	**Nematode**	**Laboratory /field experiment**	**Efficacy**	**Reference**
Spodoptera frugiperda, Helicoverpa gelotopoeon	*S. diaprepesi*	Lab		Caccia et al., [20]
Cotton bollworm (*Helicoverpa armigera*)	*S. feltiae*	Lab, Glasshouse	75%-90%	Glazer & Navon, [140]; Glazer [41];Navon et al., [142]; Shahina et al. [143]; Ebrahimi et al., [144]
Corn earworm, *Helicoverpa (=Heliothis) zea*	*S.riobravis* *S.carpocapsae*	Field	90%	Cabanillas & Raulston, [145]; [146]; [22];[147];1996
Corn earworm, (*Heliothis zea*)	*N.carpocapsae* DD-136	Field	58%-88%	Bong & Sikorowski, [148]; Bong [149]
Pink bollworm (*Pectinophora gossypiella*)	*S.carpocapsae* *S.riobrave* *H.bacteriophora* HP88	Lab	76.43%- 86.45%	Lindegren et al., [150] Shairra & Nouh, [112]; Shairra et al., [76]
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., [27];[151];[152];[153]
Pink bollworm, (*Pectinophora gossypiella*)	*S.riobravis*	Field	25.7-92.4%	Jech & Henneberry, [154]
Codling moth (*Cydia pomonella*) (diapausing larvae)	*S. carpocapsae* Sal *S. feltiae* Umea S. *riobrave*	Lab, Field	94.4%-94.7%	Dutky and Hough, [4]; Kaya et al.,[29]; Nachtigall & Dickler, [34]; Lacey & Unruh, [8]; Lacey & Chauvin, [37]; Vega et al., [155]; Unruh, & Lacey, [30];Lacey et al., [38];[156]; De Waal et al. [157,158]

Pest	Nematode	Laboratory /field experiment	Efficacy	Reference
	H. zealandica *H.bacteriophora*			
Codling moth (*Cydia pomonella*)	*S.feltiae* *S.carpocapsae* *S.yirgalemense* *H. zealandica*			Sledzevskaya, [35] Cossentine et al., [36]; Lacey et al.,[33]; [159] Malan et al., [160] De Waal, [161]; De Waal et al., [162], [163,164], [165] Odendaal et al., [166]; [167] Ahmad et al., [168]
	H.pakistanensis NBAIR H-05	Field	43.85 -86.27 %	
	S. carpocapsae Bakişli *S. feltiae* ES-3 *H.bacteriophora* TOK20 *H. bacteriophora* 11-KG	Lab	71.5%-82.63%	Yagci et al., [169]
Filbertworm, (*Cydia latiferreana*)	*S. carpocapsae*	Lab, Field	65%-92%	Chambers et al., [170]
Carob moth (*Ectomyelois ceratoniae*)	*S.carpocapsae* *S. feltiae*	Lab	76.5% 79.75%	Memari et al., [171]
Diamond backmoth (*Plutella xylostella*)	*S.carpocapsae* All *S.riobravis*	Lab , greenhouse, Field	79.1%	Baur et al.,[172,173] Shinde &Singh, [174]; Singh & Shinde, [175]
	S.carpocapsae	Lab		Ratnasinghe &Hague, [176]; Schroer & Ehlers, [177]; Schroer et al., [178]
	H.indica *S.karii* *S.wesieri*	Lab	86.7%-96.0%	Nyasani et al., [179,180]
	S.carpocapsae *H. bacteriophora*	Lab	72.6%–96%	Zolfagharian et al., [181]

Pest	Nematode	Laboratory /field experiment	Efficacy	Reference
	H. bacteriophora BA1 *S.carpocapsae* BA2	Greenhouse	64.4%- 79.8%	Hussein et al., [182]
Potato tuber moth, (*Phthorimaea operculella*) (second ,fourth instar larvae , prepupa)	*S.carpocapsae* *S. feltiae* *S. glaseri* *S. bibionis* *H. bacteriophora*	Lab		Ivanova et al.,[183]; Hassani-Kakhki et al., [184].
Potato tuber moth, (*Phthorimaea operculella*)	*S.carpocapsae,* *S. feltiae,* *H. bacteriophora*	Lab	40%-100%	Lacey & Kroschel, [185]; Kepenekci et al., [186]
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, [187]
Red hairy caterpillar, (*Amsacta albistriga*)	*Steinernema* sp. *H. indica*	Lab Microplot	80% 42%	Prabhu & Sudheer, [188]
False codling moth (FCM), (*Thaumatotibia Leucotreta*)	*S. yirgalemense* *S.khoisanae* *H. zealandica* *H. bacteriophora*	Lab Field		Manrakhan et al., [189]; Malan & Moore, [190]; Malan et al., [160];[191]
False codling moth (*Thaumatotibia Leucotreta*)	*S. yirgalemense* *H. zealandica* *S.litchii*	Lab	93.5%-100%	Steyn et al., [192]
Dalaca pallens	*S. australe* QU N3 *S.unicornum* QU N13	Lab	95%-100%	Maldonado et al., [193]
Sugarcane early shoot borer, (*Chilo infuscatellus*)	*H.indica* LN2 *H. bacteriophora* LN8 *Heterorhabditis* sp. HII *S.carpocapsae* *S. glaseri*	Lab		Sankaranarayanan et al., [194]

Pest	Nematode	Laboratory /field experiment	Efficacy	Reference
	S. riobrave *S. feltiae*			
Earias insulana *Heliothis armigera* *Spodoptera littoralis*	*S.carpocapsae* Mexican	Field	85%-95%	Glazer & Navon, [195];1990 Glazer et al., [17,140]
Mexican rice borer (*Eoreuma loftini*)	*S. riobravis*	Lab Field	100%	Legaspi et al., [196]
Brazilian apple leafroller (*Bonagota Salubricola*)	*H. bacteriophora* RS107 *H. bacteriophora* RS57	Lab Field	61.1%-70.2%	Negrisoli et al., [139]
Mocis latipes	*H. bacteriophora*			Gonzalez-Ramirez et al., [197]
Ostrinia furnacalis *H. armigera* *S. litura*	*S.abbasi* MBLB *S minutum* *S. tami* *H. indica* PBCB	Lab	28.15%-100%	Caoili et al., [92]
wax moth, (*Galleria mellonella*) yellow meal worm, (*Tenebrio molitor*) beet armyworm, (*Spodoptera exigua),* black cutworm, (*Agrotis ipsilon*), European corn borer, (*Ostrinia nubilalis*)	*S. carpocapsae* *S. glaseri* *S. feltiae* *S. riobravis* *H.bacteriophora*	Lab		Caroli et al., [198]
Spodoptera exigua *Pseudaletia unipuncta*	*S. feltiae*	Lab	68%-100%	Kaya, [29]
Spodoptera exigua (prepupae , pupae , adults)	*N.carpocapsae*	Lab		Kaya & Grieve, [60]
Stem borer of maize (*Sesamia calamistis*)	*H.* sp.	Lab	4-57%	Claudius-Cole, [69]
Fall armyworm	*S. carpocapsae* All Mexican	Lab	1%-28%	Espky & Capinera, [135]

Pest	**Nematode**	**Laboratory /field experiment**	**Efficacy**	**Reference**
(*Spodoptera frugiperda*), greater wax moth (*Galleria mellonella*), black cutworm (*Agrotis ipsilon*)				
Pseudaletia unipuncta	*H.bacteriophora* *S. carpocapsae* *S. glaseri*	Lab		Rosa et al., [199]
Rice leaf folder, (*Cnaphalocrosis medinalis*)	*N. carpocapsae* DD-136	Lab		Srinivas & Prasad, [200]
Ghost moth (*Hepialus californicus*)	*H.hepialus*		72%	Strong et al., [201]
Navel orange worm (*Amyelois transitella*)	*S. carpocapsae* *S. feltiae*	Field	72%	Siegel et al., [41]
European corn borer, (*Ostrinia nubilalis*)	*N. carpocapsae* DD-136	Lab, Field		Lewis &Raun, [132]
Melonworm, (*Diaphania hyalinata*)	*S. carpocapsae*			Shannag & Capinera, [202]

across all EPNs concentrations. It seems that developmental events during the pupal stage might influence infective juvenile penetration rates" [207]. Acharya et al. [21] "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*."

3. 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.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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