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A review of insect-parasitic nematodes research in India: 1927–1997

(*Keywords:* insect pests, biological control, nematodes, India)

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Abstract. In the last 70 years, over 100 articles have been published on mermithid nematodes from a wide range of insects. More than 16 species of allantonematids have been reported from insects within the orders Coleoptera, Thysanoptera, Lepidoptera and Hymenoptera. *Howardula* species have been studied in detail on thrips and beetles, but the data obtained are insufficient to allow us to conclude whether or not these nematodes are potential biocontrol agents. Research on entomopathogenic nematodes started in 1966 and much of the available information is on the DD 136 strain of *Steinernema carpocapsae*. Critical information on the entomopathogenic nematode fauna of India, and on their efficacy under field conditions, is not available. A review of the overall progress made in India on nematodes as biocontrol agents of insects reveals a lack of research focus and direction. This paper summarizes progress to date and suggests ways of encouraging the use of nematodes as bioinsecticides in India.

1. Introduction

Insects cause considerable damage to field and orchard crops. The use of chemical pesticides to control these pests has gradually expanded, and the recent world insecticide sales (including acaricides) is estimated at 6.0 billion US $ per annum (Georgis and Hague, 1991). However, sole reliance on chemical pesticides is not sustainable because of the associated problems of environmental degradation, development of insect resistance, pest resurgence, and secondary pest outbreaks due to elimination of natural enemies. Due to the environmental hazards they present, many insecticides have been withdrawn from the market. Clearly, other effective and environment-friendly methods of insect control, such as the use of natural enemies and host plant resistance, need to be developed. Fortunately such developments have gained momentum in recent years. The annual growth increase in chemical insecticide use is 1 – 2%, compared with 10 – 25% for microbial insecticides (Ahmed and Leather, 1994). The role of microbial pesticides (*sensu lato*, i.e. bacteria, fungi, nematodes, protozoa, and viruses) in agriculture and forest protection has expanded considerably with the discovery, development and genetic improvement of microbial strains and improvement of their formulation and application methods. (Lacey and Goettal, 1995). When used as a part of IPM programmes, microbial insecticides offer viable, safer and ecologically-based alternatives (Hom, 1996). This paper reviews the status of progress made with nematodes and discusses the likely future directions to be adopted to enhance their use in India.

1.1. The insect-parasitic nematodes

Biocontrol of insects with nematodes has progressed significantly since Glaser (1932) discovered Japanese beetles infected with *Steinernema glaseri*. Since then, many species of nematodes pathogenic to insects and other invertebrates have been found (Poinar, 1990). The most commonly found insect parasitic nematode species belong to the families Allantonematidae, Mermithidae, Steinernematidae and Heterorhabditidae. Currently, entomopathogenic nematodes account for more of the biopesticides marketed in the industrialized countries than all the other organisms combined, apart from *Bacillus thuringiensis* (Bedding, 1996). While in many developed countries entomopathogenic nematodes are at a commercial production stage with identified markets, India lags far behind. An allantonematid, *Beddingia* (Syn. *Deladenus*) *siricidicola* , is being successfully used against a European wood wasp *Sirex noctilo* introduced into Australia and New Zealand (Bedding, 1992). A mermithid nematode, *Romanomermis culicivorax* was briefly sold commercially in the 1970s. However, it was commercially unsuccessful because of environmental limitations (Petersen, 1984). In contrast, nematode species within the families Steinernematidae and Heterorhabditidae are commercially more successful. They are uniquely associated with symbiotic bacteria, which occur in the intestine of the nematodes. When these nematodes enter the body cavity of insects, the nematodes release the bacteria, which cause septicemic death of the insects. These nematodes have been successfully developed as microbial biocontrol agents of insects particularly those inhabiting soil and cryptic habitats (Gaugler and Kaya, 1990; Georgis, 1992). Currently, *Steinernema carpocapsae*, *S. feltiae*, *S. glaseri*, *S. riobravies*, *S. scapteriscae*, *Steinernema* sp., *Heterorhabditis bacteriophora* and *H. megidis* are available commercially in different countries (Hom, 1994).

1.2. The agroecological regions and pesticide use in India

India is a tropical country and has a climate conducive for insect pests. It has very diverse agroclimatic conditions ranging from the humid, high rainfall northeastern zone to northwestern semi-arid and arid zones. Based on rainfall, geomorphological features, vegetation, cropping systems and land use, 20 agroclimatic zones are recognized within the country (Sehgal *et al.*, 1996). Insect pests are widespread in all the agroclimatic zones and large quantities of insecticides are used to control these pests. Approximately 52 000 MT (metric tonnes) of

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Table 1. List of insect-parasitic nematodes reported from India

Nematode species	Insect species	Susceptible host stage	Reference
Allantonematids (Tylenchids)			
Contortylenchus sp.	Rutelidae	Adult females	Muthukrishnan, 1976
Heterotylenchus crassirostris Yatham and Rao	*Musca crassirostris* Stein, *Stomyxis calcitrons* (L.)	Larvae and adults	Yatham and Rao, 1981
Heterotylenchus hyderabadensis Reddy and Rao	*Morella hortensia* Widemann	Adults	Reddy and Rao, 1980
Howardula albopunctata Yatham and Rao	*Sepsis* spp.	Adults	Yatham and Rao, 1980
Howardula aptini (Sharga)	*Microcephalothrips abdominalis* Crawford, *Frankliniella schultzi* Trybom	Nymphs and females	Varatharajan, 1985
H. aptini (Sharga)	*Megaluriothrips* sp.	Nymphs and females	Reddy *et al*., 1982
Howardula belgaumensis Raj and Reddy	*Longitarsus belgaumensis* Jacoby	Grubs	Raj and Reddy, 1989a
Howardula marginatus Reddy and Rao	*Copromyza* sp.	Females	Reddy and Rao, 1981
Howardula multilatus Devi, Rao and Reddy	*Carpophilus* sp.	Grubs	Devi *et al*., 1991
Howardula phyllotreta Oldhan	Coleopteran, *Phyllotreta chotanica* Duv.	–	Devi *et al*., 1980
Howardula saginata Rajashekar, Rao, Reddy and Reddy	*Monopleta* sp.	Females	Rajashekhar *et al*., 1995
Howardula truncata Remullet and VanAwerebeke	*Carpophilus* sp.	Grubs	Rukminidevi and Rao, 1982
Neotylenchid	*Scirpophaga nivella* (Fabrius)	–	David, 1962
Schistonchus racemosa Reddy and Rao	*Ceratosolen* sp.	Females	Reddy and Rao, 1986
Stictylus sp.	*Chilo partellus* (Swinhoe)	Larvae	Muthukrishnan, 1976
Tylenchid (unidentified)	*Phlebotomus papatasii* Scopoli	Adults	Srinivasan *et al*., 1992
Mermithids			
Agamermis sp.	*S. incertulus* (Walker)	Caterpillar	Rao, 1964
Agamermis sp.	*S. incertulus* (Walker)	Caterpillars	Rao *et al*., 1968
Agamermis sp.	From citrus orchard soils	Caterpillar	Varma and Yadav, 1974
Agamermis sp.	*Lymantria obfuscata* Walker	Caterpillar	Dharmadhikari *et al*., 1985
Agamermis sp.	*Cnphalocrocis medinalis* (Guenee)	–	Manoharan and Chandrashekar, 1986
Geomermis indica Steiner	*Pempherulus affinis* Faust	Grubs	Ayyer, 1940
Hexamermis sp.	*Onthophagus* sp.	–	Varma, 1966
Hexamermis sp.	–	Larvae	Rao *et al*., 1968
Hexamermis sp.	*Chrysopa* sp., *Dilinia* sp., *Thiacidas* sp, *Inderbela* sp.	Caterpillars	Mehra *et al*., 1968
Hexamermis sp.	*Spodoptera mauritia* (Bois.)	Larvae	Murad, 1969
Hexamermis sp.	*Fodina stola* Guen., *Hypena iconicalis* Wlk., *Phytometra* sp., *Hypocola rostrata* Fab., *Achaeae janata* L., *Epispari*s sp., *Hyblaea puera* Cram, *Cephanodes* sp., *Terias blanda silhetana* Wall, *Platynopus* sp., and unidentified lepidopteran	Larvae	Gokulpure, 1970
Hexamermis sp.	*Nilaparvata lugens* Stal.	Nymphs	Manjunath, 1978
Hexamermis sp.	*Helicoverpa armigera* (Hubner)	Caterpillar	Divaker and Pawar, 1982
Hexamermis sp.	*Serinatha augur* (Fabr)	–	Dhiman, 1984
Hexamermis sp.	*Chilo infuscatellus* (Snell.), *Scirpophaga nivella* (Fabricius), *Chilo sacchariphagus indicus* (Kapur)	–	Srivastava, 1964
Hexamermis sp.	*A. janata* L., *C. partellus* (Swinhoe), *Cydia* spp., *Lampedes boeticus* L., *Mythimna separata* (Walker), *S. incertulus* (Walker), *Spodoptera litura* (Fabricius), and *Spodoptera exigua* (Hubner)	Caterpillars	Bhatnagar *et al*., 1985
Hexamermis sp.	*Cydia* sp.	–	Subbiah, 1986, 1989
Hexamermis sp.	Forest insect pests	–	Sandhu *et al*., 1993
Hexamermis sp.	*Cydia hemidoxa* Myrick	Caterpillars	Devasahayam and Abdullah-Koya, 1994
Limnomermis sp.	*Neochetina* spp.	Pupae	Ghode, 1987
Mermis sp.	*Amsacta moorei* (Butler)	Caterpillars	Bindra and Kittur, 1956
Mermis sp.	*A. moorei* (Butler), *Cirphis* sp., *Sara* sp.	Caterpillars	Bindra and Kittur, 1957
Mermis sp.	*Helopeltis theivora* Waterhouse	Nymphs	Mukherjee and Raychowdary, 1956
Mermis sp.	*C. infuscatellus* (Snell.)	–	Ali, 1957
Mermis sp.	–	Adults	Sen and Dasgupta, 1958
Mermis sp.	Epilemid, Eucosmid, Hyblaeid, Notodontid, Pierid, Psychild, Sphingid, Chrysomelid, Acridid, geometrids, noctuids, pyralids	Larvae	Mathur, 1959

(continued)

Table 1 (concluded).

Nematode species	Insect species	Susceptible host stage	Reference
Mermis sp.	*Spodoptera exigua* (Hueber)	–	Khan and Hussain, 1964
Mermis sp.	*Atrichopogan* sp., *Chironomous* sp.	–	Dasgupta, 1964
Mermis sp.	*Antigastra catalaunalis* (Dup.)	Caterpillars	Patnaik and Das, 1969, Jakhmola and Yadav, 1975
Mermis sp.	*Anopheles culicifacies* Giles	–	Prakash and Hussainy, 1975
Mermithid (unidentified)	*Anopheles* sp.	–	Iyenger, 1927
Mermithid (unidentified)	*Schoenobius incertellus* Walker	Caterpillars	Khan *et al.*, 1956
Mermithid (unidentified)	*H. armigera* (Hubner)	Caterpillars	Mundiwale *et al.*, 1978
Mermithid (unidentified)	*Anopheles* sp.	Larvae	
Mermithid (unidentified)	*Nisia* sp	–	Jayanthi *et al.*, 1987
Mermithid (unidentified)	*Leptocoris* sp.	–	Padmanabhan and Chaudhary, 1990
Mermithid (unidentified)	*Coccinella septemunctata* L.	Grubs and beetles	Rhamhalinghan, 1992
Ovamermis sp.	*H. armigera* (Hubner), *H assulta* (Guenee), *H. peltigera* Schiff	Caterpillars	Bhatnagar *et al.*, 1985
Pentatomermis sp.	*Nezara viridula* L.	Larvae and adults	Bhatnagar *et al.*, 1985
Romanomermis iyengari Welch	*Culex tritaeniorhynchus* Giles, *Anopheles* sp.	Larvae	Welch, 1964, Paily and Jayachandran, 1987; Paily *et al.*, 1991, 1994; Achutan, 1988; Paily and Balaraman, 1990, 1993, 1994
Romanomermis sp.	*Culex fatigans* Weid. *Anopheles* sp, *Aedes aegypti* L., *Armigeres* sp.	Larvae	Gajanana *et al.*, 1978; Bheema Rao *et al.*, 1979; Chandrahasan and Rajagopalan, 1979; Edward *et al.*, 1979
Romanomermis culicivorax Ross and Smith	*C. fatigans* Weid.	Larvae	Sharma and Gupta, 1982
Rhabditids			
Panagrolaimus sp., and *Rhabditis* sp.	*C. partellus* (Swinhoe)	Caterpillars	Mathur *et al.*, 1966
Panagrolaimus sp.	Lepidopteran larval gallery	–	Muthukrishnan, 1976
Panagrolaimus mygophilus Poinar and Geetha Bai	*Musca domestica* L.	Larvae	Poinar and Geethabai, 1979
Parasitorhabditis sp.	*Sesamia inferens* (Walker), *Chilo auricilius* Dudgeon, *S. incertulas* (Walker)	Larvae	Nayak *et al.*, 1977, 1983
Pelodera sp.	*M. domestica* L.	Larvae	Geethabai and Shankaran, 1985
Pelodera sp.	*Rhynchophorus* sp.	–	Muthukrishnan, 1976
Rhabditis sp.	*Oryctes rhinoceros* (L.)	–	Kurian, 1967
Rhabditis sp.	*Odontotermes obesus* (Rembur)	–	Muthukrishnan, 1976
Rhabditis sp.	*Holotrichia serrata* Fabrius	–	David *et al.*, 1986

–, Not specified.

technical grade pesticides are used annually to develop various formulations (Rajak, 1992). Indiscriminate use of insecticides, lack of adequate knowledge on proper application techniques and dosages, and frequent use of broad spectrum insecticides are common in India. There is a compelling need to develop and propogate environment- and user-friendly options for insect pest management.

2. Research on entomopathogenic nematodes in India

2.1. Allantonematid nematodes

The work on allantonematids (tylenchid) insect parasitic nematodes started in India in 1962. The allantonematids were reported as parasites of insects within the orders Coleoptera, Thysanoptera, Lepidoptera and Hymenoptera (table 1). David (1962) reported an allantonematid insect parasitic nematode (unidentified neotylenchid species) from *Scirpophaga nivella*. Subsequently, Muthukrishnan (1976) reported an association of tylenchid nematode species with important insect pests. In the 1980s, the life cycle and population dynamics of two species of *Heterotylenchus* and four species of *Howardula* were reported (Devi *et al.* 1980; Reddy and Rao, 1980; Yatham and Rao, 1980; Reddy *et al.*, 1982; Rukminidevi and Rao, 1982; Varatharajan, 1985). The allantonematids were recorded from thrips and beetles. *Howardula aptini*, a parasite of thrips, occurs throughout the year, the greatest prevalence of the parasite being recorded during high population densities of thrips. Nymphs and females of thrips are susceptible to this nematode, and infected females have fewer developing eggs in the ovaries

(Reddy *et al.*, 1982; Varatharajan, 1985). The life cycle, nature of parasitism, occurrence and distribution of *H. aptini* indicate that it is a potential biocontrol agent under natural conditions (Rukminidevi and Rao, 1982). Four other species of *Howardula* are parasites of coleopterans. The first or second stage grubs of Coleopterans are parasitized by juveniles of *Howardula* sp. (Rukminidevi and Rao, 1982). The infected beetles have a low reproductive potential. *Howardula belgaumensis*-infected insects also have low fecundity, and they have smaller ovaries (Raj and Reddy, 1989a).

2.2. Mermithids

Mermithids are obligate parasites of insects. Mermithids were the first insect parasitic nematodes reported from India from *Anapheles* mosquitoes (Iyengar, 1927, 1938). *Geomermis indica* was isolated from the grubs of *Pempherulus affinis* in 1940 (Ayyer, 1940). There were no further mermithid reports until the late 1950s, and research on *Romanomermis* sp. was started with the identification of a new species of *Romanomermis iyengari* from Tamil Nadu (Welch, 1964). In the 1970s, a group of researchers at the Vector Control Research Centre, Pondicherry was actively involved in the use of *Romanomermis* species for mosquito control (Gajanana *et al.*, 1978; Bheema Rao *et al.*, 1979; Chandrahasan and Rajagopalan, 1979; Paily and Jayachandran, 1987; Paily and Balaraman, 1993, 1994; Paily *et al.*, 1994). Reports of mermithids in different insect hosts have continuously appeared since the late 1970s. Species of the genera *Agamermis, Geomermis, Hexamermis, Limnomermis, Mermis, Ovamermis, Pentatomermis*, and *Romanomermis* have been identified parasitizing a wide range of insects of economic importance (table 2). Except for *Romanomermis* sp, over 70% reports are mere records of association with the insect hosts. The insect hosts are generally from within the orders Coleoptera, Hemiptera, Diptera and Lepidoptera. The mermithid-infected insect dies soon after the nematode completes development inside the insect body and emerges by piercing the cuticle. Under natural conditions, the prevalence of parasitism by mermithids was reported to be between 12% in rice planthopper and 66% in the lepidopteran. *Amsacta moorei* (Bindra and Kittur, 1956; Jayanthi *et al.*, 1987). High levels of mermithid parasitism is generally observed in moist and moderate temperature conditions (Bindra and Kittur, 1956; Jakhmola and Yadav, 1975; Manoharan and Chandrashekar, 1986; Raj and Reddy, 1989b; Devasahayam and Abdulla-Koya, 1994). *Hexamermis* spp. are frequent natural parasites of lepidopteran insects, more on alfisols than on vertisols, with greater incidence of insects feeding on low-growing crops such as groundnut, tomato and weeds (Bhatnagar *et al.*, 1985).

2.3. Other nematodes

A few species of rhabditid nematodes, other than steinernematids and heterorhabditids, have been reported from house fly, maize stem borer, paddy stem borer, red palm weevil, rhinoceros beetles and ragi pink borer (table 1). Mathur *et al.* (1966) were the first to report these nematodes from insects in India. Since then about 10 reports have been published. *Panagrolaimus* spp. were reported from the alimentary canal of *Chilo zonellus* and from a lepidopteran larval gallery (Mathur *et al.*, 1966; Muthukrishnan, 1976). Life cycles of the two parasitic nematodes, *Panagrolaimus mygophilus* and *Pelodera* sp., on *Musca domestica* were studied by Geethabai and Shankaran (1985). All larval stages and adults of *Musca domestica* are susceptible to *P. mygophilus*, first and second stage instars are more susceptible. The nematode completes its life cycle within 5 days and completes two to five generations in the same host. All stages of *Musca domestica*, except egg and pupae, are susceptible to *Pelodera* sp. (Geethabai and Shankaran, 1985). These species have been reported from the insect's internal body organs (Kurian, 1967) and from abdominal folds. *Parasitorhabditis* species recovered from the larval stages of *Sesamia inferens* caused high mortality of *Tryporyza incertulus* and *Chilo auriculus*, when artificially inoculated. The nematode was easily cultured on high protein cattle feed and on nutri nugget, a soyabean preparation with 50% proteins (Nayak *et al.*, 1977, 1983).

2.4. Steinernematidae and Heterorhabditidae

Work on steinernematids in India was first started in 1966 (table 2). Rao and Manjunath (1966) discussed the use of the DD 136 strain of *Steinernema carpocapsae* in the control of insect pests of rice, sugarcane and apple. Consequently, a group of workers at the Central Rice Research Institute, Cuttack initiated work on DD 136 for the biocontrol of rice insect pests. This group actively worked with DD 136 on applied aspects such as mortality of the insect pests in laboratory and field trials, life cycle of the nematode, and compatibility of DD 136 with insecticides and fertilizers. Other workers (Singh and Bardhan, 1974; Singh, 1977) worked on similar aspects in the 1970s. However, this trend declined in the mid-1980s. An average of one research article per year has been published from India. Overall progress of work has not followed any definite trend.

The heterorhabditid group has been relatively recently identified from (Tamil Nadu) India (Sivakumar *et al.*, 1989). These nematodes are cultured on larvae of the wax moth (*Galleria melonella*), rice moth (*Corcyra cephalonica*) and on dog biscuits. Rice moth is more commonly used because of a simple culturing procedure based on autoclaved coarsely ground maize grains. Although there are several reports of entomopathogenic nematodes (table 2) parasitizing insect pests of rice, maize, groundnut, potato, with a wide host range including species of *Spodoptera*, *Helicoverpa*, *Amsacta* and *Holotrichia* , field data are very limited.

2.4.1. Efficacy of entomopathogenic nematodes for management of major crops pests

2.4.1.1. Rice. Israel *et al.* (1969a) observed high mortality of paddy cutworm (*Pseudoletia separata*) and leaf folder caterpillar (*Cirphis compta*) when inoculated with the DD 136 strain (*Steinernema carpocapsae*) in laboratory, glasshouse and field experiments. Other important rice pests such as paddy stem borer (*Tryporyza incertulus*), Asian rice borer (*Chilo suppressalis*), ragi pink borer (*Sesamia inferens*), paddy butterfly (*Melanitis ismene*), rice skipper (*Paranara mathias*), rice leaf folder (*Cnaphalocrocis medinalis*) and gall midge (*Pachydiplosis oryzae*) were also highly susceptible. The DD 136 strain completes its life cycle in 5 – 7 days on paddy stem borer; all stages except the egg stage of *T. incertulus* are susceptible. At higher temperatures (31 – 40°C), the nematodes are ineffective in controlling *T. incertulus* (Rao *et al.*, 1971). Srinivas and Prasad (1991) reported 98% mortality of the fifth instar larva of the rice leaf roller by *S. carpocapsae*. Addition of 2% glycerine and agar solutions to the nematode spray suspension is effective in enhancing the efficacy of nematodes (Yadava and Rao, 1970). The DD 136 strain is tolerant to concentrations of fertilizers and some common insecticides that prevail in rice fields (Rao *et al.*, 1975). The tolerance level for osmotic stress (salinity index 20 mm/mhos/cm) is also higher than the tolerance level of rice crop (Das, 1977).

2.4.1.2. Maize. Mathur *et al.* (1966) reported that caterpillars of stem borer or maize (*Chilo zonellus*) parasitized by *Neoaplecta-*

Table 2. List of steinernematid and heterorhabditid nematodes reported from India

Nematode species	Host insect species	Observations	Reference
Steinernema carpocapsae Weiser *(=Neoaplectana carpocapsae)*	*Scirpophaga incertulas* (Walker)	Field trials	Rao and Manjunath, 1966
Steinernema sp.*(=Neoaplectana* sp.)[a]	*Chilo partellus* (Swinhoe)	Occurrence	Mathur *et al.*, 1966
S. carpocapsae Weiser *(=N. carpocapsae)*	*S. incertulus* (Walker), *Mythimna separata* (Walker), *Spodoptera compta* (Moore)	Field trials for efficacy	Israel *et al.*, 1969a
S. carpocapsae Weiser *(=N. carpocapsae)*	Noctuidae	Mortality tests in laboratory and fields	Israel *et al.*, 1969b
S. carpocapsae Weiser (DD 136 strain)	Rice insect pests	Nematode life cycle, efficacy in fields, medium for application, attraction towards insects, steps involved in infection	Yadava and Rao, 1970
S. carpocapsae Weiser (DD 136 strain)	Arctidae, Lymantinidae, Noctuidae, Pyrulidae	Mortality tests in laboratory	Mathur *et al.*, 1971
S. carpocapsae Weiser *(=N. carpocapsae)*	*S. incertulas* (Walker)	Mortality tests in microplots	Rao *et al.*, 1971
S. carpocapsae Weiser (DD 136 strain)	*Athalia proxima* (Klug.), *Aulacophora* foveicollis (Lucas), *Spilarctia obliqua* (Walker), *Dysdercus* sp, *Helicoverpa* armigera (Hubner), *Leucinodes orbonalis* Guenee, *S. litura* (Fabricius)	Compatibility with agrochemicals and IPM	Singh and Bardhan, 1974
S. carpocapsae Weiser (DD 136 strain)	–	Compatibility with insecticides and fertilizers	Rao *et al.*, 1975
S. carpocapsae Weiser (DD 136 strain)	–	Effect of osmotic stress on nematodes	Das, 1977
Steinernema sp. *(=Neoaplectana* sp.)[a]	*Agrotis* sp., *Agrotis segetum* (Schiff.) and white grubs	Occurrence and mortality tests in laboratory	Singh, 1977
S. carpocapsae Weiser (DD 136 strain)	*Anomala* sp.	Mortality tests	Sunderababu *et al.*, 1984
S. carpocapsae Weiser (DD 136 strain)	–	Temperature effect on storage	Sunderababu *et al.*, 1985
S. carpocapsae Weiser (DD 136 strain)	–	Compatibility with pesticides	Das and Divaker, 1987
S. carpocapsae Weiser (DD 136 strain)	*Spodoptera litura* (Fabricius), *H. armigera* (Hubner), *Chilo partellus* (Swinhoe), *Partellia* sp.	Test of application methods in lab experiments	Gupta *et al.*, 1987
Steinernema feltiae Filipjev	*S. litura* (Fabricius)	Susceptibility of different stages investigated	Narayanan and Gopalakrishnaan, 1987
S. feltiae Filipjev	*H. armigera* (Hubner), *Mylabris pustulata* (Thunberg)	Integration with NPV	Narayanan and Gopalakrishnaan, 1988
S. feltiae Filipjev	*H. armigera* (Hubner)	Mortality tests in laboratory	Ghode *et al.*, 1988
Heterorhabditis bacteriophora Poinar	*S. litura* (Fabricius) *Orthocris simulans, Drasterius* sp., *H. armigera* (Hubner) *Papilio* sp., *Ergotis* sp.	Morphometrics of nematode mortality of hosts	Sivakumar *et al.*, 1989
S. carpocapsae Weiser	*Cnphalocrocis medinalis* (Guenee)	Mortality of different instar stages	Srinivas and Prasad, 1991
Heterorhabditis sp.[a]	*Scirpophaga excerptalis* (Walker)	New species	Poinar *et al.*, 1992
S. feltiae Filipjev[a]	*S. litura* (Fabricius)	Occurrence. mortality tests	Singh *et al.*, 1992
Steinernema sp.	*Papilio* sp.	Mortality in lab and field experiments	Singh, 1993
S. carpocapsae Weiser[a], *H. bacteriophora* Poinare[a] and *Heterorhabditis* sp.[a]	*Amsacta albistriga* (Walker)	Mortality in lab and field experiments	Bhaskaran *et al.*, 1994
S. feltiae Filipjev	*Pieris brassicae* (L.), *Aphitobius* sp, *Oryzaephilus* sp.	Infectivity tests	Mathur *et al.*, 1994

[a]Populations reported from India.

na sp. (=*Steinernema*) were distinctly sluggish, inactive and stopped feeding in late stages of infection. The colour of the caterpillars changed from whitish to brown and black when dead.

2.4.1.3. Potato. Populations of cutworm (*Agrotis ipsilon*) are parasitized by *Neoaplectana* sp. The symptoms of infection are similar to bacterial septicemia. A 100% mortality of *A. ipsilon* and *A. segetum*, and 75% mortality of white grubs (*Holotrichia* sp.) may occur (Singh, 1977). The DD 136 strain can cause 100% mortality of potato chafer grub (*Anomala* sp.) (Sunderababu *et al.*, 1984).

2.4.1.4. Groundnut. Bhaskaran *et al.* (1994) tested the effects of DD 136 strain, the Burliar strain of *Heterorhabditis bacteriophora* (a local strain from Tamil Nadu) and the Chekkanurnai and Melur strains of *Heterorhabditis* sp. (a local strain from Tamil Nadu) on fourth instar larvae of red hairy caterpillar (*Amsacta albistriga*) in field trials. The DD 136 strain was most effective followed by the Chekkanurnai strain of *Heterorhabditis* sp. and the Burliar strain of *H. bacteriophora*. The LC_{50} values, determined in Petri dishes on filter papers, ranged between 6.5 and 19.4 infective juveniles/larva. The Melur strain of *Heterorhabditis* was ineffective.

2.4.2. Efficacy of entomopathogenic nematodes on other polyphagous insect pests

2.4.2.1. Tobacco cutworm. Singh and Bardhan (1974) recorded 66% mortality of tobacco cutworm, *Spodoptera litura* larvae when the DD 136 strain was inoculated at the rate of 125 infective juveniles/five larvae in Petri dishes on filter paper. All instar/larvae are susceptible to DD 136 strain (Gupta *et al.*, 1987). The LC_{50} value is 19 infective juveniles of *H. bacteriophora* (Burliar strain) for *S. litura* fourth instar larvae (Sivakumar *et al.*, 1989). Prepupae and adults of *S. litura* are more susceptible than the pupae; young 1-day-old pupae are more susceptible than 2 – 5-day-old pupae (Narayanan and Gopalakrishnaan, 1987).

2.4.2.2. Gram pod borer. Gram pod borer (*Helicoverpa armigera*) is a preferred host of DD 136 strain (Gupta *et al.*, 1987). Singh and Bardhan (1974) found 58.2% mortality of larvae of *H. armigera* when inoculated with 125 DD 136 juveniles/five larvae in Petri dishes on filter paper. Nematode populations may vary in their pathogenicity (Ghode *et al.*, 1988). However, 100 infective juveniles/10 larvae is an effective dose for *H. armigera*. Greatest mortality of *H. armigera* occurs when nuclear polyhedrosis virus and DD 136 together infect the insects (Narayanan and Gopalakrishnaan, 1988).

2.4.2.3. Other insects. High mortality (53–73%) in populations of brinjal fruit borer (*Leucinodes orbonalis*), mustard sawfly (*Athalia proxima*), vegetable pest (*Aulacophora foveicollis*) and red cotton bug (*Dysdercus cingulatus*) was observed when treated with DD 136 at the rate of 125 infective juveniles/five larvae in Petri dishes on filter paper (Singh and Bardhan, 1974). Castor semi-looper (*Paralellia algira*) is highly susceptible to DD 136 (Gupta *et al.*, 1987). Sivakumar *et al.* (1989) found that adult grasshoppers (*Orthacris simulans*), and larvae of the beetle, *Draterius* sp., citrus butterfly (*Papilio aristolochiae*) and *Ergolis merione* are highly susceptible to parasitism by *H. bacteriophora* (Burliar strain).

2.4.3. Compatibility of entomopathogenic nematodes with other components of insect IPM

Trials on compatibility of entomopathogenic nematodes with insecticides and application methods have revealed compatibility of DD 136 with dimethoate, endosulfan, malathion, mancozeb and zineb at the field recommended dosage (Das and Divakar, 1987). The flood jet nozzle is effective for spraying DD 136 under field conditions (Gupta *et al.*, 1987). The flood jet nozzle sprays more juveniles per unit time, discharges coarse droplets containing more water and helps in reducing loss due to desiccation.

3. Discussion

Of the tylenchid insect parasitic nematode species reported from India, *Howardula* species appear to be promising potential biocontrol agents of beetles and thrips under natural conditions. Studies on life cycle, ecology, behaviour, host specificity and mass culturing are needed before their widespread use can be recommended. Similarly, information on rhabditids (other than steinernematids and heterorhabditids) is insufficient for a recommendation to be made.

Mermithids are reported to be very effective against their hosts under moist and moderate temperature conditions. These conditions prevail at high altitudes, in plains during rainy and post-rainy seasons and in dense forests. In such areas, mermithids have potential as biocontrol agents. This group has not received much attention from industrialized countries due to the high costs involved in *in vivo* production. In China, *Ovamermis sinensis* was successfully used for the control of noctuid armyworm, *Mythimna separata* (Olkowski and Daar, 1989). Popiel and Hominick (1992) proposed that *in vivo* production of mermithids may be a viable option for developing countries where human resources are available at a low cost. Mermithids deserve greater attention in the Indian context.

The nematode species and strains of *Steinernema* and *Heterorhabditis* exhibit differences in survival, searching behaviour and infectivity. Therefore, there is considerable interest in finding populations with traits suitable for local conditions. A number of surveys have been conducted in many parts of the world. From tropical and subtropical regions, surveys have been conducted in Puerto Rico (Roman and Beavers, 1982), Hawaii (Hara *et al.*, 1991), Israel (Glazer *et al.*, 1991), Sri Lanka (Amarsinghe *et al.*, 1994) and Egypt (Shamseldean and Abd-Elgawad, 1994). Hominick *et al.* (1996) discussed the literature on entomopathogenic nematodes, confirming that little is known about their diversity in India. Currently, two strains, of *Steinernema* sp. and *Heterorhabditis* sp. (species unidentified), one strain each of *S. feltiae* (=*S. carpocapsae*) and *H. bacteriophora*, and a new species, *Heterorhabditis indicus*, have been reported from India (Poinar *et al.*, 1992). The reported strains have not been adequately evaluated for their efficacy as biocontrol agents. The Central Rice Research Institute, Cuttack and Central Integrated Pest Management

Centre, Hyderabad, Andhra Pradesh have been culturing DD 136 strains on rice moth larvae and supplying them to rice growing farmers for field application against rice pests. However, data on application dosages and field efficacy are not available. Thus, overall information on field data is very limited. Bedding (1990) suggested strategies for development of entomopathogenic nematodes in developing countries, most of them applicable to India. These suggestions should be followed to enhance the use of entomopathogenic nematodes in the management of insect pests in India.

Investigations of insect parasitic nematodes have been conducted in India since 1927 (Iyengar, 1927) and lack of direction and focus is evident. There has never been a concerted effort to develop these organisms as a viable option for insect pest management. There is great potential and scope for isolating strains of nematode species which are highly virulent pathogens. The immediate priority is to assess the natural diversity in the gene pool of insect parasitic nematodes present in different agroclimatic regions. This should enable identification of nematode strains that are well adapted to local climates, as well as providing faunistic information. Hominick *et al.* (1996) discussed sampling procedures and limitations in studies on the biodiversity of entomopathogenic nematodes. With standard techniques, relative infectivities of different species and strains can be tested (Popiel and Hominick, 1992). After obtaining LD_{50} values from pot experiments, field experiments need to be conducted and, if results are encouraging, properly designed multilocational trials should be initiated. For small-scale rearing of nematodes, *Galleria* larvae and white traps can be used, and for large-scale rearing, liquid or solid cultures are cost effective.

Private industries, National Agricultural Research Systems (NARS), Non-Governmental Organizations (NGO) and International Agricultural Research Centres (IARC) could be involved in producing nematode products and also popularizing them among farmers. Currently, several private companies have started production and marketing of biological control agents for insect control in India. For example, Ecomax Agro Systems is marketing two entomopathogenic nematodes with trade names Soil Commandos (*Heterorhabditis bacteriophora*) and Green Commandos (*Steinernema carpocapsae*) in India. Soil Commandos is recommended for root pests and Green Commandos for foliar insect pests. However, greater Research and Development and extension efforts are required to identify and popularize the nematode-based products for insect pest control. A synergistic collaborative programme involving the IARC, NGO and NARS is needed to foster this environmentally friendly pest management approach.

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