Journal of Biological Control, 24 (3): 185–202, 2010

Review Article

Biological control of aphids

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ABSTRACT: Biological control of aphids (Hemiptera: Aphididae) is reviewed. A brief report on the history of biological control of aphids is given. Candidate natural enemies including parasitoids, predators and entomopathogens consisting of about 12 groups are listed. Brief information about viable multiplication technologies for important species in each group is provided. Finally biological control of aphids in open fields and in glasshouses by using different natural enemies is reviewed by analyzing different attempts made in India and elsewhere. It is concluded that parasitoids in general and aphidiids in particular possess greater potential than predators and entomopathogens both in open fields and in glasshouses.

KEY WORDS: Aphids, biological control, parasitoids, predators, pathogens

(Article chronicle: Received: 23.04.2010; Sent for revision: 26.04.2010; Accepted: 26.06.2010)

1. *Economic importance of aphids*

World over 4000 aphid species have been recorded, of which 1020 are distributed in the Oriental region. Out of about 800 species described so far from India (Ghosh and Basu, 1995), less than 100 species are pests of economically important crops. *Aphis gossypii* Glover can develop on more than 400 plant species in India (Raychaudhuri, 1983). Out of 247 viral diseases of plants, 164 are stated to be transmitted by nearly 200 species of aphids (Kennedy *et al*., 1962). *Myzus persicae* (Sulzer) alone transmits more than 100 plant viruses (Eastop, 1958). Singh (2000) listed 35 species of aphids as the most economically important pests in India and abroad. In view of their short life cycle and high reproductive rate, aphids can multiply in large numbers and cause severe yield loss in economically important crop plants. Chemical insecticides have been used regularly for the management of aphid pests but not without risk of resurgence of several species of aphid pests as a consequence of application of chemical pesticides indiscriminately. Destruction of natural enemies, development of insecticide resistance and phytotoxic effects of chemical pesticides leading to high rate of multiplication of aphids have been attributed as possible reasons for aphid resurgence. At present most of the aphid pests are managed by application of chemical insecticides alone. Chemical control, though effective in the beginning, is undesirable due to problems of environmental pollution and residual toxicity. Dhingra (1993) recorded rapid change in susceptibility levels of different species to commonly used pesticides. Later, she recorded development of resistance in *Aphis craccivora* Koch, *M. persicae* and *Lipaphis erysimi* (Kaltenbach) (Dhingra, 1994).

2. *Non-chemical approaches for management of aphids*

Bakhetia and Chandler (1997) reviewed the management strategies for aphids with special reference to host plant resistance while Sachan (1997) reviewed the cultural control of aphids. Recently, Singh (2000) highlighted importance of aphid parasitoids in biological control of aphids. All these workers emphasize the need for alternative methods for effective management of aphids especially in the changing scenario of modern sustainable agriculture.

3. *Need for biological control*

One of the reasons for the increase in the number of attempts at biological control of aphids in recent years is a greater need, as a consequence of the increased incidence of invasion of new areas (between and within countries) by aphid species. Carver (1989) listed 25 species of aphids, which invaded 60 different countries from 1953 to 1987. In such instances use of natural enemies from the native areas is the only reasonable alternative for management of aphid pests.

4. Aphids as candidates for biological control

Aphids are characterized by parthenogenesis, paedogenesis, viviparity and polymorphism contributing to their high reproductive rates. Rapid reproduction allows aphids to have overlapping generations because of which the preferred developmental stages of aphids are quickly available for parasitism and predation.

Aphids being less mobile are more amenable for biological control. They and their honeydew are attractive food sources for many entomopathogens. Nevertheless their physiological activity at low temperature and frequent and rapid changes in their populations make them poor prospects for biological control. Biological control of pests tends to be long lasting and often can be implemented at little direct cost to producers and consumers. For these reasons, biological control is considered as a cornerstone of many Integrated Pest Management (IPM) programmes.

5. History of classical biological control of aphids

The advantages of biological control are numerous, especially when compared to chemical control. The method is non-polluting, non-toxic and self-perpetuating. Though the initial cost may be high, no subsequent expense is incurred and the results are generally permanent. The popularity of biological control waned after the introduction and widespread use of pesticides in the 1940s but was again renewed with the recognition of the severe limitations and dangers of chemical control.

Laing and Hamai (1976) and Van den Bosch *et al.* (1982) provided lists of biological contol projects throughout the world and Clausen (1978) gave a review of candidate pests and their agents. Hughes (1989) gave a synoptic summary of attempts at biological control of aphids in Australia and elsewhere.

Biological control of aphids was advocated way back in 1734 by De Reaumur, who recommended the collection of eggs of an aphidivorous fly (syrphids or chamaemyiids, not known) for their control in greenhouses (Simmonds *et al*., 1976). Carver (1989) summarized attempts at classical biological control throughout the world. This summary indicates that there were 27 attempts through use of parasitoids mainly aphidiids and aphelinids throughout the world (excluding India), of which 19 met with success while five were failures and results of three attempts are not known (Table 1). In these trials, the major parasitoid genera were *Aphidius* (eight species) and *Trioxys* (four species). The most successful species were *A. ervi* Haliday (five successful attempts), *A. smithi* Sharma and Subba Rao (four successful attempts) and *T. pallidus* (Haliday) and *T. complantus* Muesebeck (three successful attempts each). Similarly there have been six attempts at introduction, translocation within country and inundative releases of coccinellids throughout the world. Out of these, three attempts resulted in establishment of the coccinellid species but are not giving satisfactory control, while others are failures. The successful predatory species include a dendronilid beetle and *Hippodamia convergens*.

In India, an attempt to introduce *Aphelinus mali* (Haldeman) (Aphelinidae) from England was successful. It was first released in Shimla and now the parsitoid has been successfully colonized in the entire apple growing areas of India (Singh, 1994).

6. Natural enemies

6.1 Parasitoids

Two hymenopteran families, Aphidiidae (Ichneumonoidea) and Aphelinidae (Chalcidoidea), comprise the parasitoids of aphids, in addition to a few species from other hymenopteran families and some species of gall midges (Mackauer and Chow, 1986).

6.1.1 Aphidiidae

These are small, hymenopterous insects, with an adult size ranging from about one to several mm. They are strictly specific solitary endophagous parasitoids of aphids. Approximately 60 genera and subgenera and more than 400 species are known from all over the world. However research of the group has been rapidly progressing, so that the number of described taxa is continuously increasing (Starý, 1988). From northeast India alone, 87 species under 18 genera have been recorded (Raychaudhuri, 1990). Recently, Joshi (2005) recorded 14 species of aphidiid parsitoids and two species of aphelinid parasitoids parasitising 19 species of aphids in Karnataka. The most common genera of aphidiids are: *Adialytus* Föster, *Aphidius* Nees, *Diaeretiella* Starý, *Ephedrus* Haliday, *Lipolexis* Föster, *Lysiphlebus* Föster, *Monoctonus* Haliday, *Pauesia* Quilis, *Praon* Haliday and *Trioxys* Haliday.

6.1.2 Aphelinidae

These are rather small, chalcidoid hymenopterous insects, mostly less than 1 mm in adult size. Homoptera in particular can be parasitized by these parasitoids, of which only part has become associated with the aphids as primary and secondary hosts (Viggiani, 1984). The aphidophagous aphelinids are represented by several genera comprising a limited number of species; however, some of the genera also include parasitoids on insects other than aphids (Starý, 1988). The most common genera of aphelinids parasitising aphids are *Aphelinus* Dalman and *Mesidia* Föster.

6.2 Predators

The number of species of organisms that will prey on aphids is very large, as can be seen from the number of

Table 1. History of classical biological control of aphids

Year of introduction	Aphid species	Parasitoid species	Introduced from	Introduced into	Results
Parasitoids					
1920	*Eriosoma lanigerum* (Hausmann)	*Aphelinus mali* Haldemann	USA	51 countries	Established in 42 countries
1953	*Therioaphis trifolii maculata* (Buckton)	*Trioxys complantus* Quilis, *Praon exsoletum* (Nees) and *Aphelinus asychis* Walker	Middle East	Western Australia	All quickly established but *T. complantus* playing major role
1977	*Therioaphis trifolii maculata*	*Trioxys complantus* Quilis, *Praon exsoletum* (Nees) and *Aphelinus asychis* Walker	North America	Western Australia	All quickly established but *T. complantus* playing major role
1977	*Therioaphis trifolii maculata*	*Zoophthora radicans* (Brefeld)	Israel	Western Australia	Established
1982	*Therioaphis trifolii maculata*	*Trioxys complantus* Quilis	Australia	New Zealand	Spotted aphid is no longer a pest
1958	*Acyrthosiphon pisum* (Harris)	*Aphidius smithi* Sharma and Subba Rao	India	North America	Readily established
1963	*Acyrthosiphon pisum* (Harris)	*Aphidius ervi* Haliday	Europe	North America	Very successful but *A. ervi* has displaced earlier existing parasitoid, *A. smithi*
1978	*Acyrthosiphon pisum* (Harris)	*A. smithi*	India	Hawai, South America Europe	Results not known
1976	*Acyrthosiphon pisum* (Harris)	*Aphidius smithi, A. eadyi* Stary	India	New Zealand	*A. smithi* could not establish but *A. eadyi* is common now
1979	*Acyrthosiphon pisum* (Harris)	*Aphidius smithi, A. eadyi* Stary and *A. pisivorus* Smith	Europe	Australia	Not established
1986	*A. kondoi* Shinji	*A. ervi*	Europe	North America, Australia, New Zealand	Now widespread
1986	*A. kondoi*	*Ephedrus paligator* (Nees) *Praon barbatum* Mackaur	Europe	Australia, New Zealand	Not successful
1972, 1978	*A. pisum*	*A. ervi*	Europe	Argentina	Successful
1959	*Chromaphis juglandicola* (Kaltenbach)	*Trioxys pallidus* (Haliday)	France	California	Could not disperse beyond costal areas
1968	*C. juglandicola*	Heat tolerant strain of *T. pallidus*	Iran	California	Quickly became widespread
1984	*Myzocallis coryli* (Goez)	*T. pallidus*	Europe	Oregon, USA	Not known

(Continued from pg. 187)

Year of introduction	Aphid species	Parasitoid species	Introduced from	Introduced into	Results
1970s	Tinocallis platani (Kaltenbach)	*T. curvicaudus* Mackauer and *Eucallaphis tilliae* (Linnaeus)	Europe	California	Both established: 1st on *Tilia* while 2nd on *Ulmus*
1962	*Cavariella aegopodii* (Scopoli)	*Aphidius salicis* Haliday	California	Australia	Controlled aphid and carrot motley dwarf virus disease
1968	*Schizaphis graminum* (Rondani)	*Aphelinus asychis*	Iran	North America	Could not establish
1976	*Metopolophium dirhodum* (Walker) and *Sitobion avenae* (Fabricius)	*Aphidius ervi, Aphidius rhopalosiphi* de Stefani Perez, *Aphidius uzbekistanicus* Luzhetzki	Mediterranean France	Southern Chile	Considered as potential regulators
1985	*M. dirhodium*	*A. rhopalosipji*	England and France	New Zealand	Established
1986	*M. dirhodium*	*A. rhopalosipji*	Chile and New Zealand	Australia	Not established
1981	*Hyperomyzus lactucae* (Linnaeus)	*Aphidius sonchi* Marshall and *Praon volcre* (Haliday)	Mediteranean Areas	Australia	Established
1984	*Aphis craccivora* Koch	*Lysiphlebus fabarum* (Marshall)	Mediteraneun areas	Australia	Not recovered
1984	*Aphis craccivora* Koch	*L. testaceipes*	California	Australia	Established, also taking care of other species of aphid *T. aurantii*
1986	*Aphis craccivora* Koch	*Trioxys indicus* Subba Rao and Sharma	India	Australia	Results not known
1983	*Cinara cronarti* Tissot and Pepper	*Pauesia* spp.	USA	South Africa	Established
Predators					
Since 1993	*Adelges piceae* (Ratzeburg)	Many coccinellids and chamaemyiids	Many sources	North America	Many established but *Laricobius erichsoni* (Rosonhaur) is considered to be effective
Many attempts from 1957 to 1975	Many aphid species	*Coccinella septempunctata* Linn.	Many sources	USA	Has spread throughout two third of North America (only after 1973)
1976	Many aphid species	*Hippodemia convergens* Guerin-Meneville	North America	Peru, Chile, Venezuella, Hawaii	Established
1973-1978	Many aphid species	Translocation of many coccinellid species	Within USA		Failed
1975-1977	Many aphid species	Many species of syrphids, chamaemyiids and chrysopids	North America	New Zealand	Not known
1973	*Macrosiphum euphorbiae*	*C. septempunctata*	Within USA	Failed	

taxonomic groups that contain predators of aphids (Table 2). The proportion of predatory species in each group varies from only a few species of Anystidae and Sphecidae, to almost all species in the major subfamilies of Coccinellidae, Chrysopidae and Syrphidae.

Table 2. Groups of organisms with at least one species predatory on aphids

Group	Predatory stage
Coleoptera	
Coccinellidae	Larva, adult
Cantharidae	Adult
Carabidae	Adult
Staphylinidae	Larva, adult
Diptera	
Syrphidae	Larva
Cecidomyiidae	Larva
Chamaemyiidae	Larva
Chloropidae	Larva
Dermaptera	
All families	All mobile stages
Hymenoptera	
Vespidae	Adult
Formicidae	Adult
Sphecidae	Adult
Neuroptera	
Chrysopidae	Larva
Hemerobiidae	Larva, adult
Coniopterygidae	Larva, adult
Heteroptera	
Anthocoridae	Nymph, adult
Nabidae	Nymph, adult
Reduviidae	Nymph, adult
Pentatomidae	Nymph, adult
Capsidae	Nymph, adult
Miridae	Nymph, adult
Lygaeidae	Nymph, adult
Araneae	
All families	All mobile stages
Acari	
Anystidae	All mobile stages
Opiliones	Nymph, adult
Aves	Nymph, adult

(Frazer, 1989)

6.2.1 Coccinellidae

The coccinellid fauna of the world consists of about 420 genera and over 5000 species. Four hundred and one species belonging to 79 genera, 22 tribes and five subfamilies have been recorded so far from the Indian subcontinent (Poorani, 2002). The majority of the species are predaceous on Homoptera but they will accept a wide range of foods. Aphidophagous coccinellids are primarily found in the subfamily Coccinellinae but aphidophagy is also present in the Scymninae and Chilocorinae.

6.2.2 Syrphidae

There are more than 4700 species worldwide (Chambers, 1988) with 312 species under 71 genera known from the Indian subcontinent (Ghorpade, 1994). In Europe, most of the aphidophagous syrphids are known from two tribes, *viz*., Syrphini and Melastomini of the subfamily Syrphinae., whereas in India, the tribes Syrphini and Paragini are considered to be important. In Paragini, different species of the genus *Paragus* are widely distributed, whereas in Syrphini, *Ischiodon*, *Eupeodes*, *Dideopsis* and *Episyrphus* are important genera. From these genera, *Eupeodes corollae* (Fabricius), *Ischiodon scutellaris* (Fabricius) and *Episyrphus balteatus* (De Geer) are the most extensively researched.

6.2.3 Lacewings

Coniopterygidae (dusty or powdery lacewings), Hemerobiidae (brown lacewings) and Chrysopidae (green lacewings) are widely distributed throughout the world.

6.2.3.1 Coniopterygidae

The latest checklist (Reik, 1975) includes 450 described species, which are divided in Brucheiserinae, Coniopteryginae and Aleuropteryginae subfamilies. Of these, Brucheiserinae comprises only two species from South America, while the other two are diverse and widely distributed. Because of their small size (most are only 2-4 mm in length), they appear to be less important in an applied context, other than the control of Acarina, probably their most usual prey.

6.2.3.2 *Hemerobiidae*

Most of the species of Chrysopidae are arboreal, but many Hemerobiidae are characteristic of low vegetation, sometimes as part of a very broad habitat range. These include a number of species of the widely distributed genera *Micromus* Rambur and *Hemerobius* Linnaeus. Most of the biological information available refers to members of these genera in various parts of the world including India. It contains around 550 species of worldwide occurrence

(Oswald, 1993). As their common name implies, they are most commonly brownish or grayish and more rarely green, with a fore wing length of 3-18 mm (Oswald, 1993).

6.2.3.3 Chrysopidae

This is the most diverse family of the three. Brooks and Barnard (1990) recognized 75 valid genera to incorporate 1200 recognized species. From India, 67 species are known (Singh and Narasimham, 1992). The genera *Chrysoperla* Steinmann, *Mallada* Navás, *Apertochrysa* Tjeder and *Brinckochrysa* Tjeder have possible value as biological control agents.

6.2.4 Cecidomyiidae

Harris (1973) published a comprehensive taxonomic revision of the aphidophagous Cecidomyiidae on a worldwide basis. He included five species, *viz.*, *Aphidoletes aphidimyza* (Rondani), *A. urticariae* (Kieffer), *A. abietis* (Kieffer), *A. thompsoni* Möhn and *Menobremia terranea* (Kieffer), of which *A. aphidimyza* is the most important with 61 aphid species as hosts, many of them pests of cultivated plants.

6.2.5 Anthocoridae

Anthocoridae is represented throughout the world by over 400 species. The two genera, which are considered as the most important as predators of aphids, are *Anthocoris* and *Orius*. Both genera are widely distributed in the Northern Hemisphere, but only *A. nemorum* (Linnaeus), *A. nemoralis* (Fabricius), *A. confusus* Reuter and *O. majusculus* (Reuter) are important as predators of aphids (Hodgson and Aveling, 1988).

6.2.6 Aphidophagous Lepidoptera

Larvae belonging to the families Noctuidae, Helionidae, Pyralidae, Lycaenidae and Geometridae have been recorded as predators of aphids. Fourteen species have been recorded throughout the world feeding on eighteen species of aphids. In India, four species of predators have been recorded feeding on five species of aphids (Pierce, 1995).

6.2.7 Other invertebrates

There are several records of aphid predators from Acari (mites), Araneae (spiders), Chilopoda (centipedes), Opiliones (harvestmen), Carabidae, Staphylinidae, earwigs, Diptera (Chamaemyiidae and Chloropidae), Formicidae, Heteroptera (Nabidae, Miridae and Geocoridae), Sphecidae (Hymenoptera) and Mollusca. These predators are often neglected in pest control studies because many of them are small, cryptic and difficult to study. The predatory fauna is not adequately described for most crops, but, where this has been done, the species number is very high [e.g. about 350 species in cereals (Sunderland and Chambers, 1983); around 600 species on cotton (Whitecomb and Bell, 1964) and approximately 240 species in alfalfa (Wheeler, 1977)].

6.3 Pathogens

Insect pathogens have been reviewed by Gustafsson (1971), Hall (1981) and Wilding (1981). Their reviews include pathogens infesting scales, aphids and other insects. Latgé and Papierok (1998) reviewed aphid pathogens in particular and indicated that fungi have been considered the principal group of aphid pathogens, the most prevalent and widely encountered species belonging to the order Entomophthorales (Zygomycetes). In particular environments (greenhouse and tropical regions) deuteromycete species may also significantly reduce aphid numbers. According to Latgé and Papierok (1998), fungi should be considered as the best candidates for the biological control of aphids because they are very effective in natural and laboratory conditions; many fungal species are highly specific to aphids and totally harmless to mammals and beneficial fauna; and unlike aphid predators and parasitoids, certain species are easily produced *in vitro*. Bacteria and protozoans have not been conclusively demonstrated in aphids, but several baculoviruses and picornaviruses have been found which can be transmitted transovarially and decrease significantly the longevity of the infected individuals (D'Arcy *et al.*, 1981). However, no viral epizootics in aphids have ever been reported. The species of Entomophthorales identified from aphids belong to five genera, *viz.*, *Conidiobolus*, *Entomophthorales*, *Erynia*, *Neozygites* and *Zoophthora*, however the Deuteromycete, *Verticillium lecanii* (Zimmerman) Viégas is the most popular aphid pathogen in greenhouses. This fungus has been developed for commercial use by Hall (1981) and is produced as a greenhouse mycoaphicide under the name "Vertalec".

Several reviews on entomopathogenic fungi as candidates for biological control of aphids in general from China (Li *et al.*, 2005), Germany (Zimmerman, 1983) and Switzerland (Keller, 1977) and *V. lecanii* in particular from Benin (Alavo and Accodji, 2004) are available. Literature on other aphid fungal pathogens like *Alternaria alternata* (Christian *et al.*, 2005), *Conidiobolus obscurus* and *Erynia neoaphidis* (Latge *et al.*, 1983) and *Neozygities fresenii* (Steinkeraus, 1996) has been reviewed.

Preliminary studies on use of *V. lecanii* for biological control of aphids in glasshouses and fields from different countries like Canada (Fournier and Brodeur, 1999), Berlin (Grunberg *et al.*, 1988), UK (Hall, 1980) and Pakistan (Khalil, 1983) have been published with varying results.

7. *Rearing techniques*

7.1 *Parasitoids*

Less than 10 per cent of the known species of Aphidiidae and Aphelinidae that parasitize aphids have been reared in the laboratory. The small group which was reared includes mainly species of *Aphelinus*, *Aphidius*, *Diaeretiella*, *Ephedrus*, *Lysiphlebus*, *Praon* and *Trioxys* that have been used in biological control programmes against various economically important aphid species. The majority of these parasitoids were easy to rear on their natural or facultative hosts under average insectary conditions (Starý, 1970). Many problems that can affect mass production of aphid parasitoids are caused by difficulties in rearing aphid hosts. Simpson *et al*. (1975) have described a technique for mass production of *D. rapae* and *Praon* sp. In Europe four different companies produce *A. matricariae* commercially (Singh, 2001).

Recently in Karnataka studies were conducted on the bioecology of *D. rapae* with intention to develop its rearing techniques. The studies indicated that for effective rearing of the parasitoid, *L. erysimi* or *B. brassicae* could be used as hosts. For rearing *L. erysimi*, mustard and for rearing *B. brassicae*, cabbage, cauliflower and radish could be used. Second instar of both the aphid species is the stage to be exposed for parasitism as these are the most preferred instars. It is desirable to rear the parasitoid at a temperature range of 20 – 25°C. The adult parasitoid culture can be discarded after 10 days to economize use of aphid host and to get maximum parasitoid yield (Joshi, 2005). A series of studies has been conducted on rearing of *Trioxys indicus* on *A. craccivora* (Singh, 2000). Similarly, *D. rapae* has been studied in detail by Dhiman and Kumar (1983; 1986a; 1986b; 1986c; 1987a; 1987b; 1989).

7.2 *Predators*

7.2.1 *Chrysopids*

Mass rearing techniques for *Chrysoperla* spp. were reviewed by Nordlund and Morrison (1992). Several needs for improving existing techniques were identified. In India, Gautam (1994) reviewed the status of chrysopid rearing. According to him the processes that need improvement include larval food presentation, adult feeding and oviposition units, mechanical egg collection and de-stalking, a mechanized system for larval rearing unit preparation and field application techniques. Chrysopid species, *viz*., *Chrysoperla* (*carnea*–group), *Mallada desjardinsi* (=*M. boninensis*) and *M. astur* are being reared at the National Bureau of Agriculturally Important Insects (NBAII) since its inception (Singh and Jalali, 1991).

7.2.2 *Coccinellids*

Obrycki and Kring (1998) reviewed the status of coccinellids in biological control and stated that translocation of coccinellids from one field to other and collection and release of diapausing adults will be suitable methods for use of aphidophagous coccinellids rather than rearing them in the laboratory. In India, techniques for laboratory rearing of aphidophagous coccinellids, *viz*., *Cheilomenes sexmaculata*, *Coccinella septempunctata* and *Harmonia octomaculata* have been standardized (Joshi *et al*., 2003).

7.2.3 *Syrphids*

Efforts have been made to multiply *E. corollae* in the laboratory (Barlow, 1979; Barlow and Whittingham, 1986). In this method eggs were collected on nylon bags filled with aphids. This method failed to give good results in India. Another effort to multiply syrphids was made by Peterson (1989) who developed techniques for multiplication of *E. corollae* in glass house with controlled temperature and humidity. This method also could not be Biological control of aphids followed as such in India as it requires a lot of space and is expensive. In India, Joshi *et al.* (1998) developed techniques for mass multiplication of syrphids. Methods for mass rearing of host insect, *A. craccivora* and syrphid predators *viz*., *I. scutellaris*, *P. serratus* and *P. yerburiensis* were described. *I. scutellaris* is multiplied by following these techniques at the NBAII, Bangalore.

7.2.4 *Cecidomyiids*

Aphidoletes aphidimyza has been mass produced in different countries such as Korean Republic (Young Seol *et al*., 2003), Russia (Bondarenko, 1989) and Germany (Schmidt, 1989). In addition to this, methods for cold storage of the midge (Gilkeson, 1990) and collection of the larvae in water (Lieburg and Ramakers, 1984) have been developed. The midge is commercially available in Finland and Denmark (Nijveldt, 1988).

7.2.5 *Anthocorids*

The aphidophagous anthocorid *A. nemorum* was multiplied using different species of aphids. A complete rearing procedure including fabrication of adult rearing cage, larval rearing retreats and oviposition cartridges has been provided by Parker (1981). In India, five species of anthocorids, *viz*., *Cardiastethus exiguus* Poppius, *Blaptostethus pallescens* Poppius, *Orius tantillus* (Motschulsky) and *O. maxidentex* Ghauri associated with different aphids have been studied for their biology on different laboratory hosts. Their rearing requirements and mass multiplication techniques have been standardized

(Ballal *et al.*, 2002, 2003). Studies on their field evaluation are underway at NBAII, Bangalore.

8. *Biological control in open fields*

After releasing the natural enemy in the field, its establishment and effectiveness in bringing dawn the pest population depends on its ecological attributes. Several reviews of case histories indicated some common attributes of natural enemies leading to their successful use in biological control programme. In general, most of the reviews expect the natural enemies to possess the following characters.

1. A substantial degree of host specificity or preference for the target insect;
2. Good phenological and behavioral adaptation to the target insect population;
3. An ability to locate individuals in all parts of a target insect population and to utilize them effectively;
4. A capacity for increase which in the normal course of events allows them to overtake and suppress the target insect population;
5. Some density dependent mechanism involved in the interaction with the target insect population.

8.1 *An analysis of earlier attempts*

Of the 127 attempts made to control different aphid species biologically, nineteen were with parasitoids, seven with predators and one with fungal pathogen. Though the total attempts made are surprisingly small, the eight successes (Table 3) form a substantial proportion (Hughes, 1989).

The agents for which success has been claimed are those in which strong preference make them more or less specific to the target aphid species. Climatic matching of natural enemy and target host species seemed to be important in some cases (e.g. *Trioxys pallidus* attacking *Chomaphis juglandicola*) while it was less in others (e.g. *Aphelinus mali* attacking *Eriosoma lanigerum*). Complex life cycles of some target aphids make them somewhat immune to attack, e.g. underground stages of *E. lanigerum* were not available for attack to the natural enemy. Nearely all the enemies claimed to be successful showed very high attack rate, e.g. very high levels of attack (above 90%), were observed in the field when *T. complanatus* attacks *T. trifolii* f. *maculata*. On the other hand, very low attack rates were obtained when *D. rapae* was released against *B. brassicae*, which is not considered to be a successful example. In this case by increasing initial ratios of parasitoids to the aphids, control situations can be simulated (Hughes, 1989). In summary, the best predicator of successes for biological control of aphids in the open field is previous successful experience with the natural enemy in a similar environment. Otherwise the best chances appear to be with a climatically adapted, host-specific natural enemy that is known to attack a high proportion of the target aphid in the field.

Table 3. Substantial successes of biological control of aphids in open field

Target aphid	Natural enemy	Country of attempt	Establishment
Eriosoma lanigerum (Hausmann)	*Aphelinus mali* Haldemann	Many countries throughout the world	Established only in few circumstances
Therioaphis trifolii f. *maculata* (Buckton)	*Trioxys complantus* Quilis *Zoophthora radicans* Batko	USA USA	Rapid establishment Slow but eventual
Acyrthosiphon pisum (Harris)	*Aphidius eadyi* Starý	New Zealand	Rapid establishment
Chromaphis juglandicola (Kaltenbach)	*Trioxys pallidus* Haliday	USA	Rapid establishment
Acyrthosiphon kondoi (Shinji)	*Aphidius ervi* Haliday	Australia	Rapid establishment
Eucallipterus tiliae (Linnaeus)	*Trioxys curvicaudus* Mackauer	USA	Rapid establishment
Tinocallis platani (Kaltenbach)	*Trioxys tenuicaudus* Starý	USA	Rapid establishment

(Hughes, 1989)

8.2 *Successful attempts from India*

8.2.1 *Biological control of* A. gossypii *on cucurbits by inoculative release of* Trioxys indicus

Two inoculations at 20 days interval @ 10 mummies per m^2 twice in the crop season were made in ten different fields of *Lagenaria vulgaris*, *Luffa cylindrica* and *Cucurbita maxima* in Gorakhpur district during 1990-1992.

In these trials satisfactory control was achieved in 1990-91 and 1991-92 only on *L. vulgaris* and *L. cylindrical* but not on *C. maxima*, where inoculative releases of mummies could not increase per cent parasitism (Singh and Rao, 1995).

8.2.2 Biological control of sugarcane woolly aphid, *Ceratovacuna lanigera*

During 2002, outbreak of the sugarcane woolly aphid (*Ceratovacuna lanigera*) was noticed in the states of Maharashtra and Karnataka. By 2003-2004, this became a serious pest affecting large areas in these two states. In Maharashtra 267 thousand hectares of sugarcane were heavily infested by the aphid, with the districts of Sangli, Satara, Kolhapur and parts of Pune and Solapur, being affected the most. In Karnataka, a total of 61 thousand hectares was affected during the same year. The districts of Belgaum and Bidar were the worst hit. The pest since then has spread to Andhra Pradesh, Tamil Nadu and Kerala in the south, and Uttaranchal and Bihar in the north (Joshi and Viraktamath, 2002).

Chemical pesticides give only temporary relief and often farmers had to spray repeatedly. Apart from being uneconomical, indiscriminate use of chemicals can result in environmental pollution, mortality of natural enemies and toxicity hazards to those involved in spraying operations.

8.2.2.1 Natural enemies

By the year 2004, several natural enemies were found feeding on the woolly aphid. Thirty-one species of predators and seven parasitoids have been recorded to attack the woolly aphids. Of them, a neuropteran predator, *Micromus igorotus*, and a lepidopteran predator, *Dipha aphidivora* were found to rapidly colonize woolly aphid infested sugarcane fields and reduce the pest populations.

The syrphid, *Eupeodes confrater* was also found to feed on the woolly aphid in fairly good numbers in the cold season. A few species of ladybird beetles too feed on the woolly aphid. A parasitoid, *Encarsia flavoscutellum* brought from Assam has established well in Mandya district of Karnataka.

8.2.2.3 Conservation

Since natural enemies were found to control the woolly aphid effectively, farmers were advised not to apply chemical insecticides. In areas where chemical pesticides were not applied, the natural enemies multiplied rapidly and devoured the woolly aphid preventing outbreak situations. Therefore, chemical pesticides should not be sprayed particularly in areas where predators are present.

8.2.2.4 Augmentation

Early colonization by predators as the population of aphids begins to build up can control the pest successfully. Therefore frequent monitoring of the pest will enable early detection of the pest. If the natural enemies are not seen, the predators may be collected from areas of abundant occurrence and released for early suppression of the pest.

8.2.2.5 Mass production of predators

A simple method of mass production of *Dipha* and *Micromus* on aphids grown in shade nets was developed.

Method: Erect field cages of size 5 x 5 meters made up of 50 per cent shade net and bamboo poles on a six-month-old sugarcane crop colonized by the aphids. After the aphid has multiplied and covered the plant to an extent of 60 to 70 per cent, release 50 grown up larvae or pupae of *Dipha / Micromus*. The predators will multiply on the developing aphid populations and about 1500 to 2500 predators can be harvested from a single cage in about 60 days. The cages can be relocated to fresh locations for further production of the predators. During periods of pest abundance, the predators can also be multiplied on woolly aphids in the laboratory.

Experiments in farmers' fields have shown that release of either 1000 larvae of *Dipha* or 2500 larvae of *Micromus* per hectare as soon as the occurrence of woolly aphids is seen resulted in very good control of the pest in 45-60 days. Releases should, however, be repeated based on recurrence of the pest (Rabindra *et al*., 2006).

8.2.2.6 Biocontrol strategies for woolly aphid management

1. Apply only the recommended doses of chemical fertilizers. Excessive application of nitrogenous fertilizers will result in the outbreak of aphids.
2. Monitor the sugarcane crop for early detection of the pest. The aphid outbreak occurs in patches, particularly in shady areas where the humidity is higher.
3. If predators are present, conserve them by avoiding spraying of chemical pesticides.
4. Since *Micromus* pupates in the leaf sheaths of the lower leaves, the detrashed leaves should not be

burnt but left behind in the field to allow the adults to emerge.

6. If predators are not seen, release *Dipha* (1000/ha) or *Micromus* (2500/ha) two – three times depending on the incidence of the pest (The pest population will be controlled within 60 days).

8.2.3 Field efficacy of entomopathogenic fungi against mustard aphid, Lipaphis erysimi *(Kaltenbach) on* Brassica campestris

Different strains of *Beauveria bassiana* (Balsamo) Vuillemin, green muscardine fungus, *Metarhizium anisopliae* (Metschnikoff) Sorokin and *V. lecanii* were used at Pantnagar, India against *L. erysimi* infesting *B. campestris* var. brown sarson. All the fungi reduced more than fifty per cent population of *L. erysimi*. However, amongst different fungi, maximum per cent reduction was observed in *V. lecanii* at 5 x 10^{10} after 10 days of first spraying followed by *M. anisopliae*. More than 100 per cent *B. campestris* yield increased over control in *V. lecanii* at 5 x 10^{10} treated plots (Purwar and Sachan, 2004).

9. Biological control in greenhouses

9.1 Major aphid pests in greenhouses

One or more aphid species are potential pests for most of the crops grown in protected conditions. *Myzus persicae* is the most common species, attacking a wide range of host plants followed by *Aphis gossypii* on cucurbitaceae, *Nasonovia ribisnigri* (Mosley) on lettuce, *Aulacorthum solani* (Kaltenbach) and *Macrosiphum euphorbiae* (Thomas) on various, mainly solanaceous crops and complex of species including *M. persicae*, *Macrosiphoniella sanborni* (Gillette), *Brachycaudus helichrysi* (Kaltenbach) and *Aphis* spp. on chrysanthemum (De Brouwer, 1976).

9.2 Why aphids become pests in greenhouses?

The overlapping of different types of cultures (vegetables, plant propagations, year-round ornamentals) and the short duration of interruptions between successive cultures in greenhouse industry allows polyphagous aphid species to breed fast, produce several generations and become serious pests. Populations originating from immigrating alates will also complete more generations than in the fields. Aphids are also favoured by extreme reproductive capacities due to high rate of development and the absence of weather dependent mortality. An increase up to 6-fold in one week was found for *M. persicae* on chrysanthemum (Wyatt, 1970), and a 7-fold increase on brinjal (Rabasse *et al*., 1983). *Aphis gossypii* populations grow even faster, increasing about 10-fold in one week (Wyatt, 1970).

9.3 Role of natural enemies in greenhouse

9.3.1 Parasitoids

Aphidius matricariae Haliday is the most widespread hymenopterous aphid parasitoid in greenhouses. Tremblay (1974) reviewed the studies on the potency of this aphidiid parasitoid as a control agent for greenhouse culture. It has been reared from as many as 40 different aphid hosts, but is the most effective against *M. persicae*. The main reasons for its success are its faster development, high oviposition frequency and total fecundity. One female wasp can produce up to 400 eggs. Assuming that half of this progeny are males, the number of females per female is thus 150, compared to 80 for *M. persicae*. Moreover, the aphidiid is able to parasitize dozens of aphids per day, whereas the daily production of the aphid is only 5 to 6 nymphs. Several other hymenopterous aphidiid parasitoids, *viz*., *Aphidius ervi* Haliday, *Ephedrus cerasicola* Starý and *A. colemani* Viereck were compared with *A. matricariae*. However, all these species were found to be inferior (Ramakers, 1988).

9.3.1.1 Use of "Banker Plants" in biological control of aphids in glasshouses

The emerging concept in biological control of aphids in greenhouses is use of "banker plants" or "open system rearing". The method involves introduction of plants with a species of aphid that could not become a pest on greenhouse crop. These aphid species help easy and early establishment of parasitoids targeted at greenhouse aphid pest. Efforts have been made to introduce barley seedlings infested with *Schizaphis graminum* which can enhance the early establishment of *Aphidius colemani* in the greenhouse and could prolong the control of *Aphis gossypii* on cucurbits in UK (Bennison and Corless, 1992). Similar attempts have been made in Switzerland (Fischer and Leger, 1997), France (Boll *et al*., 2001) and Korea (Kim and Kim, 2003).

9.3.2 Predators

A drawback of using predators in glasshouses is their need for a rather high prey density, requiring their introduction with high initial numbers and thus mass-rearing in considerable numbers. Moreover, they are not well adapted to the environmental conditions in protected cultivation.

The only example of successful predator in glasshouse is the cecidomyiid, *Aphidoletes aphidimyza*. It has been found to produce self-perpetuating populations, moreover the absence of wind and the high humidity in greenhouses favor the fragile adults, which are usually inconspicuous outdoors. It feeds exclusively on aphids and as it has wide host range, it is possible to build up a stock on non-pest species in glasshouses. Aphids die immediately after the attack, even when they are not sucked completely. Overkill by the midge larvae occurs in case of high aphid populations, but the midge can also develop on relatively small numbers of aphids.

Two main disadvantages are reported by Harris (1982), i.e., a relatively low fecundity and reproduction by unisexual families; however, this can be avoided by mass rearing and multiple releases. Other limiting factors as pointed out by Havelka (1980) are (a) mass rearing can be done only on natural hosts, (b) the predator maintains permanent population but does not prevent new outbreaks and (c) the predator needs long day conditions to prevent diapause.

9.3.3 Fungi

Many authors assume that greenhouse cultures have optimal conditions for the study of the epidemiology of pathogenic fungi. Few attempts have been made to use them as control agents. Laboratory studies on susceptibility of many aphid species followed by successful control experiments on chrysanthemum (Hall and Burges, 1979) showed that *V. lecanii* is able to bring about persistent control. This led to the development of a commercial product called Vertalec, manufactured by the British company Tate & Lyle Ltd. (Gardener *at al*., 1984). In various countries *V. lecanii* is used on a more or less experimental scale, but more often against whiteflies than against aphids, with varying results.

9.4 Successful attempts

Parasitoids

Successes of biological control of *M. persicae* in glasshouses were reported by Ramakers (1980); Popove *et al*. (1987), van Lenteren and Woets (1988), Shijko (1989), Gilkenson (1990b) and van Schelt *et al*. (1990) through *A. matricariae*. Hagvar and Hofsvang (1991) listed the attempts at use of parasitoids in greenhouse for biological control of aphids (Table 4).

Predators

In Soviet Union good results were obtained by using *A. aphidimyza* in the control of *A. gossypii* on cucumber (Nijveldt, 1998). The effectiveness of the midge against *M. euphorbiae* and *M. rosae* (Linnaeus) in commercial rose planting and against *M. persicae* on *Capsicum* and tomatoes was documented in Finland (Markkula and Tiittanen, 1977). Hansean (1983) reported successful control of *M. persicae* on sweet pepper in Denmark.

Fungi

Some encouraging results in controlling greenhouse aphids with natural (Dedryver, 1979) or artificial (Latgé *et al*., 1983) inoculum were achieved. The best results were obtained in chrysanthemum crops, where the daily periods of high humidity were lengthened by sprinkling

Table 4. Use of aphid parasitoids (Aphidiidae) in biological control of aphids in glasshouses

Parasitoid species	Aphid species	Crop	Country	Reference
Aphidius matricariae	*Myzus persicae*	Brinjal	France	Rabasse *et al*., 1983
Aphidius matricariae	*Myzus persicae*	Chrysanthemum	UK	Wyatt, 1985
Aphidius matricariae	*Myzus persicae*	Sweet pepper	UK	Buxton *et al*., 1990
Aphidius matricariae	*Myzus persicae*	Sweet pepper	Netherlands	Ramakers, 1989
Aphidius matricariae	*Myzus persicae* *Aphis gossypii* *Macrosiphum euphorbiae*	Cucumber	Netherlands	Van Lentern and Woets, 1988
Aphidius matricariae	*Myzus persicae*	Vegetables, ornamentals	Germany	Albert, 1990
Aphidius sp.	*Myzus persicae*	Not known	Hungary	Polgar, 1987
Aphidius matricariae	*Myzus persicae*	Sweet pepper	USSR	Popov *et al*., 1987
Aphidius matricariae	*Myzus persicae* *Aphis nasturtii*	Not known	Bulgaria	Longinova *et al*., 1987
Aphidius matricariae	*Myzus persicae*	Tomatoes	Canada	Gilkson, 1990
Ephedrus cerasicola	*Myzus persicae*	Sweet pepper	Norway	Hagvar and Hofsvang, 1990

(Hagvar and Hofsvang, 1991)

water and covering the plants with polythene sheets (Hall and Burges, 1979).

10. Cold storage of natural enemies

Storage of natural enemies has practical importance in biological control of aphids because (1) sufficient number of natural enemies must be secured by accumulating them for timely release (2) It is a simple method for keeping the natural enemies alive when they are of no use.

In case of parasitoids, mummies and adults can be kept at low temperature (Starý, 1970). Several workers have studied the effect of cold storage on the emergence of adult aphidiid parasitoids and were successful in conserving mummies for over a month. Also there are several studies on storage of different stages of different species of predators (Table 5) for varying periods.

11. Conservation

A 2-year study was conducted to evaluate the role of winter wheat, *Triticum aestivum* L., as a potential relay crop to conserve arthropod natural enemies and suppress cotton aphids, *Aphis gossypii*, in seedling cotton. The results suggested that the natural enemies that moved from the adjacent wheat fields to cotton fields with the maturity and harvest of wheat could keep the cotton aphid population at the edges (0-4 m) of cotton fields under the action threshold of 100 aphids/m^2. Data also suggested that the wheat strip served as a reservoir to conserve arthropod

Table 5. Cold storage of parasitoids and predators of aphids

Predator species	Storage Temperature (ºC)	Stage stored	Duration of storage	Survival (%)	Reference
Parasitoids					
Ephedrus cerasicola	0	Mummy	42 days	More than 60	Hofsvang and Hagvar, 1977
Aphidius colemani	4	Mummy	7 days	More than 60	Hofsvang and Hagvar, 1977
Aphidius matricariae	4	Mummy	30 days	More than 60	Scopes *et al*., 1973
Aphidius matricariae	1–2	Mummy	23 days	More than 60	Polgár, 1986
Aphidius uzbekistanicus	3	Mummy	28 days	More than 60	Rabasse and Ibrahim, 1987
Lysiphlebus testaceipes	4.4	Mummy	15 days	More than 60	Archer *et al*., 1973
Trioxys indicus	4	Mummy	30 days	More than 60	Singh and Srivastava, 1988
Diaeretiella rapae	4	Mummy	40 days	60	Shukla, 1999.
Lysiphlebus delhiensis	4	Mummy	30 dyas	76	Mishra and Singh, 1998
Predators					
Harmonia axyridis	4-8	Adult	4 months	84	Seo and Youn, 2002
Aphidoletes aphidimyza	5	Last instar larva/pupae	2 months	91	Gilkeson, 1990
Adalia bipunctata	6	Diapausing adults	7 months	70	Hamalainen, 1977
Coccinella septempunctata	10	Eggs	1 week	No marked reduction in hatching	Hamalainen and Markkula, 1977
Adalia bipunctata	10	Eggs	2 week	No marked reduction in hatching	Hamalainen and Markkula, 1977
Chrysoperla carnea	5	Diapausing adults	3 week	97	Tauber *et al*., 1993
Chrysoperla carnea	10	Eggs	15 days	71	Bakthavatsalam *et al*., 1995

predators and "relayed" its predators to cotton when wheat matured (Men *et al*., 2004).

Recently biological control of cereal aphids in North America was reviewed (Brewer and Elliott, 2004). The review highlights examples of habitat manipulations, within and bordering cereal fields and within the broader landscape in which cereal production resides, affecting predators and parasitoids of cereal aphids. These mediating effects of habitat manipulations on cereal aphid biological control provide significant and under explored avenues to optimize cereal aphid management.

An experiment conducted in Germany during 1995-97 evaluated the efficacy of flowering strips to reduce aphid population in apples by attracting beneficial arthropods. Grass mixture as ground cover was established on half of an apple (cultivars Golden Delicious and Fiesta grafted on M9) orchard while a mixture of 17 flowering crops was sown on alleys as alternate to grass strips on the other half of the orchard. *Dysaphis plantaginea* was the most dominant pest, followed by *Aphis pomi* and *Rhopalosiphum insertum*. Greater infestation by *D. plantaginea* was observed in plots with flower strips than grass cover. *D. plantaginea* population was always higher than the population of its predators, as the predator number increased only at the beginning of June. *A. pomi* infestation in plots with flower strips or grass cover did not significantly vary. In 1996, however, the population of beneficial arthropods exceeded that of *A. pomi*. NeemAzal (0.3% at 1000 litres/ha) reduced the population of *D. plantaginea* in 1996 and 1997 (by approximately seven-fold). In 1996, syrphid species collected from the flowering strips from July to September represented 11 genera and 14 species. *Sphaerophoria scripta* was the most dominant (40.5%), followed by *Episyrphus balteatus* (27.5%) and *Melanostoma mellinum* (17.7%). *Platycheirus clypeatus* (5.5%), *Metasyrphus corollae* [*Eupeodes corollae*], and *Eristalis tenax* were subdominant (Vogt and Weigel, 1999). Obrycki and Kring (1998) reviewed the status of predaceous coccinellidae in biological control. For conservation of coccinellids they advised use of selective pesticides, use of pest resistant varieties, landscape designing and provision of food supplements.

Vegetation management for syrphids

To enhance the effectiveness of syrphids, vegetation management is advocated, which includes planting floral source which will provide additional nectar, pollen and shelter and planting alternate prey source which will provide preys infesting warm season cover crops and cool season cover crops management (Buggs, 2000). It was concluded through his studies that local oviposition by syrphids may be more strongly influenced by shelter than by flowers, though there are some conflicting data. It is difficult to demonstrate the effects of flowers, probably because adult syrphids are highly mobile, and benefits acquired by pollen feeding (e.g., ovariole development) do not occur immediately. Moreover, nectar is an energy food and enables dispersal. Therefore, landscape-scale experiments may be needed to find out effectiveness of different factors in vegetation management.

12. Genetic improvement of natural enemies

Hoy *et al*. (1989, 1990) and Hoy and Cave (1991) developed a strain of *Trioxys pallidus*, a walnut aphid parasitoid in California, resistant to guthion and azinphos-methyl. The potential of the parasitoid may also be enhanced either by selective hybridization or through mutagenesis, recombinant DNA technology*, etc.*

13. Manipulation of behaviour

13.1 Use of semiochemicals

By application of kairomones in the fields infested with aphid pests at low-density level, the female parasitoid can be retained for longer period on the treated plants. The retention and activation increases the chances of host contact and result in increased host mortality. Also, the parasitoid can be attracted towards the infestation site by applying the kairomone, e.g. female *Praon volucre* responds to the sex pheromones of the aphid host and thus may be attracted in the fields by putting traps containing such lures (Upadhyay *et al*., 1997). Hagvar and Hofsvang (1991) listed 10 parasitoids, which get attracted to and use honeydew of aphids for location of their host.

13.2 Development of flightless strain of Harmonia axyridis

An attempt to produce a non-flying population of *Harmonia axyridis* by the use of a chemical mutagen and selection of adults with wing malformations through their subsequent generations was made. These adults are characterized by open elytra and extended wings. The mutation is either unexpressed or results in malformed wings. It also seems recessive and lethal when homozygous. The adults with the mutation suffered a high level of mortality and a drastic reduction in reproductive capacity that prevents their mass rearing for biological control. This study revealed a negative relationship between wing malformations and reproductive capacity. Nevertheless, when adults with the mutation were released in greenhouses containing cucumbers infested with *A. gossypii*, they remained on the plants in higher numbers and laid eggs over a longer period of time than the control adults but their progeny were less numerous (Tourniaire *et al*., 2000)

Summary

- Aphids are good candidates for biological control as they and their honeydew are attractive food sources for many entomophages. However, some workers believe that they are poor prospects because of their high reproductive capacity and physiological activity at low temperature.

- Attempts at classical biological control through parasitoids indicated 70 per cent success mainly through use of aphidiids, *Aphidius* being the most successful genus. Introduction, translocation and inundative release of coccinellids resulted in establishment, but not satisfactory control, in only 50 per cent of the total attempts made.
- Substantial proportion of the attempts (30 per cent) met with success when biological control was tried in open fields. Here too, aphidiids were the main control agents, *Trioxys* being the most successful genus.
- Predators in general and coccinellids in particular have not been found to be successful mainly because of ecological asynchrony between them and their prey. The main factor is temperature, which has differential effects upon rates of predation and reproductive rates of aphids. The studies suggest that predators only follow aphid abundance but arrive too late or leave too early to be effective as regulators.
- On the other hand, parasitoids being the most host-specific, better adapted, synchronized in interrelationships and having lower food requirement per individual, can maintain a balance with their host species. Also their larvae do not need to search for food.
- Many species of aphid parasitoids have been applied several times as natural enemies of glasshouse aphids. The most widely used species has been *A. matricariae*. It has better searching efficiency at low aphid density, faster development, higher oviposition frequency and total fecundity.
- The only successful predator in glasshouses is the cecidomyiid, *A. aphidimyza*. It is able to produce self-perpetuating populations and greenhouse environment is favorable for the fragile adults. Parasitoids have better searching efficiency but this predator is more successful at higher aphid density.
- Entomopathogenic fungi were found to be useful in glasshouses only in instances where daily periods of high humidity were lengthened by sprinkling water and covering the plants with polyethylene sheets.

Future road map for enhancing biological control of aphids

- Identification of more potent strains of parasitoids with high searching ability and microbial organisms with enhanced persistence on host plants.
- Development of viable, cost effective and reproducible mass production techniques for potential natural enemies and formulation of microbials.
- Isolation of indigenous strains of pathogens with high toxicity to aphid pests, particularly for glasshouse aphid pests.
- Development of storage techniques for different stages of predators and parasitoids and development of microbial formulations with enhanced shelf life.
- Development of temperature and pesticide tolerant strains of parasitoids and UV tolerant strains of microbials
- Standardization of release rates of parasitoids, predators and determination of threshold levels for different aphid pests with reference to use of microbials.
- Interaction studies between parasitoids, predators and pathogens to work out the most compatible combination for additive effect of bioagents.

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