

REVIEW

Development and use of parasitoids (Hymenoptera: Aphidiidae & Aphelinidae) for biological control of aphids in China

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Abstract

A review of aphid parasitoids in China with special emphasis on their production, utilization, and conservation is presented with a brief history of Chinese biological control. Twenty genera, 99 species of Aphidiidae and two genera, 11 species of Aphelinidae were recorded in China. Each parasitoid is listed with a brief description of aphids, host plants, areas of study such as taxonomy, biology, bionomics, geographic distribution, rearing, and literature citations. Achievements, status, and problems in aphid parasitoid production, utilization, conservation, and future prospects are detailed for dominant aphid parasitoids such as *Aphidius gifuensis* Ashmead, *A. ervi* Haliday and *Aphelinus mali* Haldeman. Finally, opportunities and challenges of commercialization of natural enemies, especially aphid parasitoids, in China, are analyzed and discussed.

Keywords: Review, China, Aphidiidae, Aphelinidae, biological control, aphid parasitoids

Introduction

China has a long history in observing and using natural enemies for biological control of pests. More than 1600 years ago, Chinese farmers used *Oecophylla smaragdina*

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Fabricius (Hymenoptera: Formicidae) to control citrus pests (Chou 1980). In the early 20th century, under the influence of an international upsurge in biological control, a few Chinese researchers engaged in taxonomic and morphological studies of natural enemies but only a very limited number of biological control practices were put in use (Bao & Gu 1998). These studies were conducted not for the purpose of furthering the science and technology of biological control but because of individual researcher's interests.

From the 1950s to 1970s, Chinese pesticide companies could not produce enough pesticides for the burgeoning agricultural usage. Therefore, development and use of biological control methods were widely encouraged. The famous cases included use of agents such as *Trichogramma* sp. (Hymenoptera: Trichogrammatidae), *Anastatus* sp. (Hymenoptera: Eupelmidae), *Cryptolaemus montrouzieri* Mulsant (Coleoptera: Coccinellidae), *Coccinella septempunctata* L. (Coleoptera: Coccinellidae) to control a number of agricultural pests in China (Li 1984). In 1972, 80 000 ha of forests and farmlands were under biological control using natural enemies and insect pathogens (Bao & Gu 1998). However, by the 1980s, modern pesticides were introduced into the country, among which organochlorine, organophosphates, and carbamates accounted for the major part. Pesticides became a dominant control technique for agriculture, forest, and sanitary industry, because they provided immediate control and had convenient application methods.

Although pesticides became the primary means of insect control, there was still some progress in biological control in China. For instance, additional progress was made in the application, alternative hosts, *in vitro* rearing and mass release of *Trichogramma* sp. This egg parasitoid was widely used to control insect pests such as *Ostrinia furnacalis* Hübner (Lepidoptera: Pyralidae), *Heliothis armigera* Hübner (Lepidoptera: Noctuidae), *Chilo infuscatella* Snellen (Lepidoptera: Pyralidae) and *Dendrolimus* sp. (Lepidoptera: Lasiocampidae), on 700 000 ha of field crops and 1 million ha of forest (Gou 1986; Li 1986). From the mid 1990s to the early 21st century, the adverse effects of chemical pesticides on health, environment, biodiversity, and even the international trade of agricultural products were gradually recognized by governments, producers and consumers (Wei et al. 2003). At the same time, China's integration into the World Trade Organization increased the chances for multilateral trade of agricultural products, which must meet pesticide residue requirements of importing countries. Under such circumstances, ecologically based IPM and alternatives, such as biological control, and ecological management, were emphasized and promoted by the government and the public to assure food safety. Therefore, biological control acquired much more attention than before (Bao & Gu 1998).

The hymenopteran parasitoids in the family of Aphidiidae and Aphelinidae are important biological control agents of aphids worldwide (Stary 1970; Yasnosh 1976; Chen 1979; Liu 1989a). Stary (1970) reviewed the world fauna of Aphidiidae with respect to integrated control of aphids, in which many international biological control activities were included. However, information on the biological control of aphids in China was lacking, except for some information from Taiwan (Stary 1970).

Lung et al. (1955, 1960) released reports about the first case studies of the aphid parasitoid, *Aphelinus mali* Hald., as a biological control agent of *Eriosoma lanigerum* Hausmann (Homoptera: Aphididae) in the early 1950s in China. Nevertheless, it was not until the early 1980s that the study and utilization of the aphidiid parasitoid,

Aphidius gifuensis Ashmead, for control of the green peach aphid, *Myzus persicae* Sulzer (Homoptera: Aphididae) were published (Zhao et al. 1980). In the 1980s and 1990s, many aphid parasitoids were recorded and classified (Chen 1980; Chou & Xiang 1981, 1982; Zheng et al. 1985, 1987; Liao et al. 1987; Ji & Zhang 1992; Zhang & Ji 1992; Huang 1994; Gu et al. 1995, 1997), but there were little data on their ecology, application in biological control, and value in controlling aphids.

In recent years, much new information on biological control agents has been published (Bao & Gu 1998), however detailed studies on aphid parasitoids in China and their application in biological control of aphids are not available in English. When collecting information in our research on the aphid parasitoids in China, we concluded that it was necessary to summarize the existing information. Therefore, in the present paper, we review aphid parasitoids in China with special emphasis on their production, utilization, and conservation in an attempt to develop some strategies for promoting their application in agriculture and forestry.

Aphid parasitoids in China

Twenty genera, 99 species of Aphidiidae and two genera, 11 species of Aphelinidae have been recorded (Table I), most as indigenous parasitoids of aphids in agriculture and forestry. The species of *Aphidius*, *Trioxys*, *Ephedrus*, *Praon*, *Pauesia*, and *Lysiphlebus* account for 80% of recorded species in Aphidiidae, and are the major biological control agents of aphids in this family. Species of *Aphelinus* are the dominant biological control agents of aphids in Aphelinidae. They make up 91% of aphid parasitoids of recorded species in this family.

Aphid parasitoid production

Although many aphid parasitoids can be mass-produced, only a few of them have been studied in detail with respect to their biology, bionomics, mass production, mass releases, utilization and conservation (Table I). We report on these parasitoids according to the scale of their production, from small to large.

Production of Aphidiidae

Among 99 species of Aphidiidae, *Aphidius gifuensis* and *A. ervi* had been mass-produced while *Diaeretiella rapae* M'Intosh (Hymenoptera: Aphidiidae) were reared in the laboratory. Limited data are available on the field biology of other important parasitoids such as *Aphidius avenae* Haliday, *Ephedrus plagiator* Nees, *Lysiphlebia japonica* Ashmead, *Trioxys indicus* Subba and Sharma, and *T. rietscheli* Mackauer. These data include host aphids, host plants, biological characteristics in the field, parasitism and natural limitation in the field, and geographic distribution (Tian et al. 1981; Zhu et al. 1982; Xi & Zhu 1984; Zheng et al. 1985, 1987; Zong et al. 1986; Wang & Liu 1989; Zhang et al. 1990; Li et al. 1991; Gao 1994; Luo et al. 1994; Gu et al. 1995; Liu 1996; Liu & Li 1999).

In Yunnan Province, *A. gifuensis* was considered for control of the aphid *M. persicae* on tobacco. Zhao et al. (1980) produced plant seedlings, aphids, and parasitoids in simple plastic greenhouses. The temperature in the greenhouse was about 27.6°C and humidity about 80% from March to August in Yuxi Prefecture, Yunnan Province.

Table I. List of aphid parasitoids and their studies in China.

Family, genus, species	Major host aphids	Major host plants	Areas of studies	Source
Aphidiidae				
<i>Ephedrus</i> Haliday				
<i>E. orientalis</i>	Unknown	Unknown	Record, distribution	Stary and Schlinger (1967)
<i>E. nacheri</i> Quilis	<i>Macrosiphum avenae</i> Fabricius	Cotton, cereal crops	Classification, ecology	Zheng et al. (1985, 1987)
<i>E. persicae</i> Froggatt	<i>Aphis gossypii</i> Glov. <i>Hyalopterus amygdali</i> Blanch	Hibiscus, peach	Record, distribution	Zheng et al. (1985, 1987)
<i>E. plagiator</i> Nees	<i>M. avenae</i>	Wheat	Record, distribution, ecology	Zheng et al. (1985, 1987), Zong et al. (1986)
<i>E. lacertosus</i> Haliday	<i>M. avenae</i>	Wheat	Record, distribution	Stary and Schlinger (1967), Dong and Wang (1985)
<i>E. nelumbus</i> Dong et Wang	<i>Rhopalosiphum</i> sp. <i>Hyadaphis foeniculi</i>	Lotus and fennel	Classification	Dong and Wang (1996)
<i>E. piceae</i>	Unknown	Spruce	Record and distribution	Gu et al. (1995)
<i>Fovephedrus persicae</i> Froggatt	Aphids on fruit trees, <i>Tuberocephalus momonis</i> Matsumura	Fruit trees	Record and distribution	Gu et al. (1995), Liu (1996)
<i>E. campestris</i> Stary	<i>Macrosiphoniella sanborni</i> Gillette	Composite species	Record and distribution	Liu (1996)
<i>Praon</i> Haliday				
<i>P. pisiaphis</i> Chou et Xiang	<i>Acyrtosiphon pisum</i> Harris	<i>Medicago sativa</i>	Classification	Chou and Xiang (1982)
<i>P. prunaphis</i> Chou et Xiang	Aphids on apricot	Apricot	Classification	Chou and Xiang (1982)
<i>P. barbatum</i> Mackauer	<i>A. pisum</i> , <i>A. gossypii</i>	<i>Pisum sativum</i> wheat	Classification, ecology	Zheng et al. (1985, 1987)
<i>P. volucre</i> Haliday	<i>A. pisum</i> , <i>A. gossypii</i> , <i>M. avenae</i>	<i>Pisum sativum</i> wheat	Classification, ecology	Zheng et al. (1985, 1987), Gu et al. (1995)
<i>P. exsoletum</i> Nees	<i>Therioaphis maculata</i> Buckton	Alfalfa	Record	Zheng et al. (1985)
<i>P. orientale</i> Stary & Schlinger	<i>A. pisum</i>	<i>Pisum sativum</i> wheat	Record	Stary and Schlinger (1967), Dong and Wang (1985)
<i>P. flavinode</i> Haliday	<i>Aphis medicaginis</i> Koch	Horsebean	Record	Dong and Wang (1985)
<i>P. gallicum</i> Stary	<i>Schizaphis graminum</i> Rondani	Wheat	Record	Zheng et al. (1987)

Table I (Continued)

Family, genus, species	Major host aphids	Major host plants	Areas of studies	Source
<i>P. glabrum</i> Stary & Schlinger	<i>Aphis medicaginis</i> Koch	Horsebean	Record	Dong and Wang (1985)
<i>P. dorsale</i> Haliday	<i>Dactynotus</i> sp.	<i>Lactuca laciniata</i>	Classification	Lu and Ji (1993)
<i>P. areolatus</i> Ashmead	<i>Macrosiphoniella</i> sp.	Composite species	Record and distribution	Liu (1996)
<i>P. hubeiensis</i> Chen & Shi	Unknown	Unknown	Classification	Chen et al. (1999)
<i>P. abjectum</i> Haliday	<i>Myzus persicae</i> Sulzer	Potato	Record and distribution	Gu et al. (1995)
Parapraon Stary				
<i>P. baodingense</i> Ji et Zhang	Unknown	<i>Artemisia annua</i>	Classification	Ji and Zhang (1992)
<i>P. brachycerum</i> Zhang et Ji	Unknown	<i>Artemisia annua</i>	Classification	Ji and Zhang (1992)
<i>P. necans</i>	Unknown	Unknown	Classification	Ji and Zhang (1992)
<i>P. rhopalosiphum</i> Takada	<i>Rhopalosiphum</i> sp.	Rice and wheat	Classification	Ji and Zhang (1992)
<i>P. yomenae</i> Takada	Unknown	Unknown	Classification	Ji and Zhang (1992)
Archaphidus Stary				
<i>A. greenideae</i>	<i>Greenidea</i> spp.	Ficus	Classification, distribution	Stary and Schlinger (1967)
Monoctonus Haliday				
<i>M. woodwardiae</i>	Unknown	Unknown	Classification, distribution	Stary and Schlinger (1967)
Pauesia Quilis				
<i>P. platyclaudi</i> Zhang et Ji	<i>Cinara tujafilina</i> Del Guercio	Arborvitae	Classification, distribution	Zhang and Ji (1992), Gu et al. (1995)
<i>P. laricis</i> Haliday	<i>Stomaphis</i> sp.	Chinese pine tree	Classification, distribution	Zhang and Ji (1992), Gu et al. (1995)
<i>P. jezoensis</i> Watanabe	<i>C. tujafilina</i>	Arborvitae	Classification, distribution	Zhang and Ji (1992), Gu et al. (1995)
<i>P. pini</i> Haliday	Unknown	Larch & Pine tree	Classification, distribution	Zhang and Ji (1992), Gu et al. (1995)
<i>P. soranumensis</i> Watanabe	<i>Cinara</i> sp.	Spruce	Classification	Zhang and Ji (1992)
<i>P. unilachni</i> Gahan	Unknown	Arborvitae	Classification	Stary and Schlinger (1967), Zhang and Ji (1992)
<i>P.</i> spp.	Aphids in Lachninae subfamily	Pine tree	Record and distribution	Gu et al. (1995)
<i>P. inougei</i>	<i>Eulachnus thumbergi</i> Wilson	Pine tree	Record and distribution	Liu (1996)

Table I (Continued)

Family, genus, species	Major host aphids	Major host plants	Areas of studies	Source
<i>P. malongensis</i> Wang et Dong	Unknown	Unknown	Classification	Wang and Dong (1997)
<i>P. japonica</i> Ashmead	<i>Lachnus tropicalis</i> Vander Goot	Chinese chestnut	Classification, biology	Zu et al. (1998)
Aphidius Nees				
<i>A. salignae</i>	Unknown	Unknown	Classification, distribution	Stary and Schlinger (1967)
<i>A. longiantennatus</i> Chou et Xi	<i>A. pisum</i>	<i>Medicago sativa</i>	Classification	Chou and Xiang (1982)
<i>A. avenae</i> Haliday	<i>M. avena</i> , <i>Rhopalosiphum padi</i> L.	Cotton and Maize	Classification, bionomics, evaluation of natural effect	Tian et al. (1981), Zhu et al. (1982), Zong et al. (1986)
<i>A. ervi</i> Haliday	<i>A. pisum</i> , <i>A. dirhodum</i>	Cotton	Classification, ecology	Zheng et al. (1985, 1987), Zong et al. (1986)
<i>A. smithi</i> Sharma et Subba Rao	<i>A. pisum</i> , <i>A. gossypii</i>	<i>Pisum sativum</i>	Classification, ecology	Zheng et al. (1985)
<i>A. picipes</i> Nees	<i>M. avenae</i>	Cereal crops	Record	Zheng et al. (1985; 1987)
<i>A. absinthii</i> Marshall	<i>M. avenae</i>	Cereal crops	Record and distribution	Stary and Schlinger (1967), Gu et al. (1995)
<i>A. phragmiti</i> Liu et Ji	<i>Hyalopterus amygdali</i>	<i>Phragmites communis</i>	Classification	Lu and Ji (1993)
<i>A. cupressi</i> Wang et Dong	<i>Aphis</i> sp.	Cypress	Classification	Dong and Wang (1996)
<i>A. dianensis</i> Dong et Wang	<i>A. gossypii</i> Glov.	Hibiscus	Classification	Dong and Wang (1996)
<i>A. uzbekistanicus</i> Luzhefzki	<i>S. graminum</i> <i>M. avenae</i>	Wheat	Classification, distribution	Zheng et al. (1987), Gu et al. (1995)
<i>A. laevipetiolus</i> Gu et Zhao	<i>M. persicae</i>	Potato	Record and distribution	Gu et al. (1995)
<i>A. matricariae</i> Haliday	<i>Rhopalosiphum</i> sp.	Millet	Record and distribution	Gu et al. (1995)
<i>A. cingulatus</i> Ruthe	Aphids on poplar and willow	Poplar and willow	Record and distribution	Gu et al. (1995)
<i>A. rhopalosiphii</i> De Stefani	<i>M. avenae</i>	Cereal crops	Record and distribution	Gu et al. (1995)
<i>A. ribis</i> Haliday	Unknown	Unknown	Record and distribution	Gu et al. (1995)
<i>A. salicis</i> Haliday	Aphids on poplar and willow	Poplar and willow	Record and distribution	Gu et al. (1995)
<i>A. colemani</i> Viereck	<i>M. avenae</i>	Cereal crops	Record and distribution	Gu et al. (1995)

Table I (Continued)

Family, genus, species	Major host aphids	Major host plants	Areas of studies	Source
<i>A. eadyi</i> Chou et Xiang	<i>M. avenae</i> , <i>R. padi</i>	Wheat and Maize	Record and distribution	Gu et al. (1995)
<i>A. gifunesis</i> Ashmead	<i>M. persicae</i> <i>L. erysim</i> , <i>S. graminum</i>	Tobacco, Carrot, and wheat	Classification	Zhao et al. (1980), Zheng et al. (1985, 1987)
			Bionomics and life history	Tang (1984), Lu et al. (1993), Lu and Shi (1994), Bi and Ji (1993, 1994), Wang and Li (1996)
			Ecology and physiology	Li et al. (1991), Wu et al. (2000a,b)
			Mass production, release, utilization	Zhao et al. (1980), Xin (1986), Xin et al. (2001), Wei et al. (2001, 2003)
<i>Lysiphlebus</i> Förster				
<i>L. shaanxiensis</i> Chou et Xiang	<i>A. gossypii</i> , <i>A. laburni</i> Kaltenbach	Cotton and Bean	Classification, biology	Chou and Xiang (1982), Zheng et al. (1985)
<i>L. testaceipes</i> Cresson	<i>S. graminum</i>	Cereal crops	Classification, biocontrol, introduce	Zheng et al. (1985), Zheng and Tang (1989)
<i>L. fabarum</i> Marshall	<i>Aphis</i> sp., <i>A. glycines</i> Matsumura	Liquorice, soybean	Record and distribution	Zheng et al. (1985), Liu (1996)
<i>L. ambiguous</i> Haliday	<i>A. gossypii</i>	Cotton	Record	Zheng et al. (1985)
<i>L. confuses</i> Tremblay	<i>M. persicae</i>	Potato	Record and distribution	Gu et al. (1995)
<i>L. japonicus</i> Ashmead	<i>Coloradoa artemisicda</i>	<i>Artemisia</i> sp.	Record and distribution	Liu (1996)
<i>Lysaphidus</i> Smith				
<i>L. platisis</i> Brethes	<i>A. gossypii</i> , <i>A. craccivora</i>	Cotton	Record and bionomics	Xi and Zhu (1984)
<i>L. matsuyamensis</i> Takada	Unknown	Unknown	Record and distribution	Gu et al. (1995)
<i>L. kunmingensis</i> Wang et Dong	Unknown	Unknown	Classification	Wang and Dong (1997)
<i>Lysiphlebia</i> Stary & Schlinger				
<i>L. japonica</i> Ashmead	<i>A. gossypii</i> <i>A. craccivora</i>	Cotton, alfalfa	Classification, biology and ecology, evaluation of control effect	Tian et al. (1981), Xi and Zhu (1984), Zheng et al. (1985), Wang and Liu (1989)
<i>L. sachari</i> Chen	<i>Longiunguis sachari</i>	Broomcorn	Record and distribution	Liu (1996)
<i>L. mirzai</i> Shuja Uddin	<i>A. gossypii</i> , <i>Longiunguis sachari</i>	Cotton	Classification, ecology	Zheng et al. (1985), Gu et al. (1995)
<i>L. jiangchuanensis</i> Wang	<i>Aphis taraxacicola</i>	Dandelion	Classification	Dong and Wang (1996)

Table I (Continued)

Family, genus, species	Major host aphids	Major host plants	Areas of studies	Source
Bioxys Stary & Schlinger <i>B. japonicus</i> Stary & Schlinger	Callipterine aphids	Ficus	Record and distribution	Stary (1970)
Binodoxys Mackauer <i>B. gossypiaphis</i> Chou et Xiang	<i>Aphis gossypii</i> Glov.	Cotton	Classification, biology	Chou and Xiang (1982)
Fissicaudus Starý <i>F. hanzhongensis</i> Chou et Xian	Unknown	Unknown	Classification	Chou and Xiang (1982)
Diaeretus Förster <i>D. leucopterus</i> Haliday	<i>Protolachmus</i> sp.	<i>Pinus tabulaeformis</i>	Classification	Lu and Ji (1992)
Diaeretiella Starý <i>D. rapae</i> M'Intosh	<i>Brevicoryne brassicae</i> L., <i>M. persicae</i>	<i>Brassicae</i> spp.	Classification Ecology Bionomics	Zheng et al. (1985, 1987), Zong et al. (1986), Liu (1989c), Lu and Shi (1994)
Adialytus Förster <i>A. salicaphis</i> fitch	Aphids on poplar and willow	Poplar and willow	Record and distribution	Gu et al. (1995)
Lipolexis Förster <i>L. oregmae</i> Gahan <i>L. Chinensis</i> Chen <i>L. gracilis</i> Förster <i>L. scutellaris</i> Mackauer	<i>Oregma lanigera</i> Zehatner Unknown <i>R. padi</i> <i>A. gossypii</i> , <i>A. spp.</i>	Unknown Unknown Maize Cotton, citrus	Record and distribution Classification Classification Record and distribution	Stary (1970) Chen (1980) Stary and Schlinger (1967), Tian et al. (1981), Zheng et al. (1985) Stary (1970), Zheng et al. (1985)
Trioxys Haliday <i>T. carinatus</i> Stary & Schlinger <i>T. confucicus</i> <i>T. flavus</i> Chou et Xiang <i>T. indicus</i> Subba et Sharma <i>T. rietscheli</i> Mackauer	Carinate 3 forked aphid <i>Greenidea</i> spp. Unknown <i>A. gossypii</i> , <i>A. craccivora</i> <i>A. gossypii</i> , <i>A. laburni</i>	Unknown Ficus <i>Artemisia</i> sp. Cotton, alfalfa Cotton and Bean	Distribution Record and distribution Classification, distribution Classification, biology, hyperparasitoids Classification, biology, evaluation of control effects	Stary and Schlinger (1967) Stary (1970) Chou and Xiang (1982), Gu et al. (1995) Tian et al. (1981), Zheng et al. (1985) Zheng et al. (1985), Wang and Liu (1989)

Table I (Continued)

Family, genus, species	Major host aphids	Major host plants	Areas of studies	Source
<i>T. communis</i> Gahan	<i>A. gossypii</i>	Cotton	Classification, bionomics	Shi (1980, 1984), Zheng et al. (1985)
<i>T. asiaticus</i> Telenga	<i>A. craccivora</i> <i>Acyrtosiphon gossypii</i>	Cotton and Bean	Classification, biology	Zheng et al. (1985)
<i>T. auctus</i> Haliday	<i>A. gossypii</i>	Cotton	Record	Zheng et al. (1985)
<i>T. struma</i> Gahan	<i>A. glycines</i> <i>Megoura citricola</i>	Soybean, Ficus	Record	Sary (1970), Dong and Wang (1985)
<i>T. orientalis</i> Stary & Schlinger	<i>A. glycines</i>	Soybean, cucumber	Record	Dong and Wang (1985)
<i>T. sinensis</i> Mackauer	<i>A. craccivora</i> , <i>Toxoptera</i> sp.	Cowpea, citrus	Record	Sary (1970), Dong and Wang (1985)
<i>T. pallidus</i> Haliday	Aphids on elm	Elm	Record and distribution	Gu et al. (1995)
<i>T. acalephae</i> Marshall	Aphids on <i>Sophora</i> sp.	<i>Sophora</i> sp.	Record and distribution	Gu et al. (1995)
<i>T. glycines</i> Takada	<i>A. glycines</i>	Soybean	Record and distribution	Liu (1996)
<i>T. populi</i> Gu	<i>Chaitophorus populeti</i> Panzer	<i>Populus tomentosa</i>	Classification	Gu et al. (1997)
Papilloma Wang				
<i>P. luteum</i> Wang	<i>Kurisaka querciphila</i> Takahashi	<i>Quercus</i> sp.	Classification	Wang (1989)
Dactylonotum Chou				
<i>D. shaanxiensis</i> Chou et Xiang	Unknown	Unknown	Classification	Chou and Xiang (1981)
Aphelinidae				
Aphelinus Dalman				
<i>A. flavipes</i> Kurd.	<i>Aphis gossipy</i>	Cotton	Record	Shi (1980)
<i>A. ceratovacuna</i> Liao	<i>Ceratovacuna lanigera</i> Zehntner	Sugar Cane	Classification	Liao et al. (1987)
<i>A. curvifasciatus</i> Huang	Unknown	Unknown	Classification	Huang (1994)
<i>A. maidis</i> Timberlake	<i>Aphis sacchari</i> & <i>A. maidis</i>	Broomcorn & Maize	Classification	Huang (1994)
<i>A. tiliaphidis</i> Li et Zhao	<i>Tiliaphis shinae</i> Shinji	Unknown	Classification	Li and Zhao (1998)
<i>A. hyalopteraphidis</i> Pan	<i>Hyalopterus arudinis</i> Fabricius	Peach	Classification	Pan (1992)
<i>A. wensanus</i> Yang et Chen	<i>Rhopalosiphum rufiabdominalis</i> Sasaki	Rice	Classification	Yang and Chen (1995)
<i>A. rhopalosiphagus</i> Yang et Chen	<i>R. rufiabdominalis</i>	Rice, Wheat	Classification, biology	Yang and Chen (1995), Chen and Wang (1995), Chen and Huo (1997), Chen and Li (1998)

Table I (Continued)

Family, genus, species	Major host aphids	Major host plants	Areas of studies	Source
<i>A. mali</i> Haldeman	<i>Erisoma lanigerum</i> & <i>Aphis pomi</i> De Geer	Apple, rose vegetables	Classification Biology and Ecology	Liao et al. (1987) Kuang et al. (1989), Tang et al. (1991), Bao and Gu (1998)
<i>Protaphelinus nikolskajae</i> Jasnosh	<i>Myzus</i> sp.	Popular	Mass production and release Classification	Lung et al. (1955, 1960) Liao et al. (1987), Yang and Chen (1995)
<i>Encarsia</i> Förster <i>E. flavoscutellum</i> Zehntner	<i>C. lanigera</i>	Sugar Cane	Classification	Jiang (1986), Huang (1994)

Aphids were collected in the field from vegetables or rape (*Brassica napus* L.), and introduced onto tobacco seedlings in the greenhouses. Parasitoids, which were stored at 4°C as mummified aphids, were warmed, allowed to emerge as adults, fed, and then introduced to the greenhouse for parasitization of the aphids. After 5–6 days development, aphid mummies emerged in large numbers. They were then collected in glass tubes and stored at 4°C for future field releases.

Wei et al. (2001, 2003) reported similar studies in Yunnan Province, but the techniques mentioned were more detailed, more applicable, simpler and more systematic than the studies published earlier. The overall rearing procedure for *A. gifuensis* using tobacco seedlings as host plants and *M. persicae* as the host insect, consisted of two parts – increasing the source of the aphid and parasitoid, and mass rearing of the parasitoid (Wei et al. 2001, 2003). They designed different mass rearing greenhouses according to the scale of production and end users. For instance, large glass greenhouses, whose sizes are 5 × 10 × 2.5 m, have been used by small companies or scientific research establishments to produce natural enemies (Wei et al. 2001). Glass-topped insectary-greenhouses (1.7 × 3 × 5 m), were used to mass produce seedlings, aphids, and parasitoids to meet the demands of companies or scientists, or farmers who have relatively good income (Wei et al. 2003). The simple plastic greenhouses (1.7 × 3 × 3 m), would be suitable for use by farmers (Wei et al. 2001). All greenhouses, regardless of size, must have black ventilated nets hanging over the roof to adjust the environment inside the greenhouse to 22–28°C and 50–70% RH. Two fluorescent lamps of 30 W each were fastened onto the sidewalls and three incandescent lights of 60 W each onto the ceiling of the greenhouses to obtain a long photoperiod, either L14:D10 or L16:D8. The high ratios of parasitoids to aphids, which are 1:10 in glass-topped greenhouses or in plastic greenhouses and 1:100–200 in big greenhouses, and short exposure time to adult parasitoids would result in synchronous egg deposition and larval development of parasitoids. Parasitoid production per generation is about 2.5 million mummified aphids for one large greenhouse, 125 000 mummified aphids for a medium-sized greenhouse, and 45 000 for a small plastic greenhouse. Detailed information on field collections, facilities in greenhouses, maintenance of seedlings, aphids and parasitoids, were included in these studies (Wei et al. 2001, 2003). Moreover, for the first time, information on cost analyses was provided. The cost of producing parasitoids dropped as the size of the rearing operation increased. Daily rearing cost in the small plastic greenhouse was US\$ 0.10 per 1000 aphid mummies during an approximate 90-day rearing period (Wei et al. 2001). Whereas the daily cost of parasitoid production in the medium-sized greenhouse was \$ 0.06 and in the big glass greenhouse, \$ 0.0021 per 1000 aphid mummies during a 90- and 150-day period, respectively (Wei et al. 2001, 2003).

While *M. persicae* and tobacco seedlings were considered the best host aphids and host plants for rearing *A. gifuensis* (Wei et al. 2003), other host plants were also used to mass produce this wasp. For instance, in Fujian and Hebei Province, *M. persicae* were produced in advance in laboratory on cabbage (*Brassica oleracea* L. var. *capitata* L.), radish (*Raphanus sativus* var. L.), or broad bean (*Vicia faba* L.) seedlings, which were cultured in pots or nutrient water at 20–25°C, 70–80% RH and 16 h photoperiod (Li 1986; Xin 1986; Lu et al. 1993; Xin et al. 2001). In mass production work starting in April, aphids and parasitoids were raised on potted radish seedlings enclosed in

Perspex (polymethyl methacrylate) cages in the laboratory at 10–20°C. Using this method, an average of 1296 (maximum 3856) parasitoids could be produced on one plant (Xin 1986). In order to meet the increased demand of mass releases, Xin et al. (2001) used greenhouses that could contain 300 potted radish seedlings and were controlled at 20–25°C, 75–80% RH, and 14 h photoperiod. The optimum ratio of female parasitoid to host was 1:200 for inoculation. The total number of aphid mummies produced was estimated at 300 000 in one greenhouse. Unfortunately, the authors did not provide details on rearing costs, duration, and detailed rearing procedures.

Aphidius ervi was mass produced using *Acyrtosiphon pisum* Harris (Homoptera: Aphididae) as the host on soybean in the laboratory and field (He et al. 1983). This wasp is commonly found in southern and central Yunnan and is a dominant indigenous natural enemy of *A. pisum* in this region. Aphids and parasitoids were reared in the laboratory on soybean seedlings planted in plastic pots. The seedlings were covered with nylon bags to contain aphids. For the purpose of mass production, a simple greenhouse was constructed in a farmer's field using clear plastic sheets and the soybean seedlings were planted on the ground inside this greenhouse. Aphids were later introduced onto leaves inside the greenhouse. The parasitoids were then introduced into the greenhouse after aphids reached adequate numbers. The aphid mummies could be harvested after 2 weeks. Storage of mummified aphids at 3–10°C for 196–202 days had no significant effect on fecundity and viability. During a 2-month period from January to March, the parasitoid yield reached 200 000 (He et al. 1983).

Diaeretiella rapae (Hymenoptera: Aphidiidae) is a very important natural enemy of several aphid species including *M. persicae*, *Brevicoryne brassicae* L., *Schizaphis graminum* Rondani and *Lipaphis erysimi* Kaltenbach worldwide. However, most studies concentrated on the bionomics, biology and behavior of the parasitoid and consequently little information is known about its mass rearing and releasing methods in China (Lu & Shi 1994; Liu 1985, 1989c, 1990; Bao & Gu 1998). The favorable host aphids include *B. brassicae* and *M. persicae*. Cabbage is a suitable host plant for aphid and parasitoid rearing in the laboratory at $\pm 25^\circ\text{C}$, 16L:8D photoperiod (Lu & Shi 1994).

Shi (1984) reported the first study on the bionomics of *Trioxys communis* Gahan (Hymenoptera: Aphidiidae). The host aphid was *Aphis gossypii* Glov on cotton. The cotton seedlings were cultured in a nutrient solution (Knop's solution) in the laboratory. After cotton aphids were transferred onto the leaves, a glass cage was used to cover the seedlings. Thereafter, *T. communis* could be introduced into the cage for parasitization and rearing.

Lysiphlebus testaceipes Cresson (Hymenoptera: Aphidiidae) was introduced from Oklahoma, USA, to Shaanxi Province in 1983. Several aphid species, including *Schizaphis graminum*, *Aphis gossypii*, *A. craccivora* Koch, *A. rumicis* L., *Rhopalosiphum padi* L., and *R. maidis* Fitch, were tested as hosts in the laboratory (Zheng & Tang 1989). This was the first report on the introduction of an aphid parasitoid from another country for aphid control in China. A small-scale experiment for mass releases was conducted (see below), but the authors did not provide information on which aphid, plant, and facilities were used for producing this parasitoid.

Production of Aphelinidae

Aphelinus mali Hald. is the only aphid parasitoid in Aphelinidae that was produced in the laboratory (small-scale) and greenhouse (large-scale) for control of the woolly apple aphid, *Eriosoma lanigerum* Hausmann (Homoptera:Aphididae). Overwintering *Aphelinus mali* were collected from apple trees in Tsingtao, Shantung province and reared in the laboratory (Lung et al. 1955, 1960). The optimal temperature for the parasitoid development is between 22 and 27°C, and the most favorable humidity ranged from 80 to 90% RH in the laboratory and rearing room situations. In order to promote the parasitoid's vitality, the authors hybridized the local Tsingto race with a USSR race, collected from the Crimea region of Ukraine. The studies showed that hybrids of this parasitoid possessed a higher reproductive potential and longer longevity than those of the local race. They also developed a field rearing technique. Branches of apple trees, 5–6-year-old, were first inoculated with woolly apple aphids and then enclosed into nylon textured bags. *Aphelinus mali* was later introduced inside the nylon bag for mass production of the parasitoid in the field. The studies conducted by Kung et al. (1989) showed that woolly apple aphid and apple twigs are the proper aphid and host plant for studying the bionomics of *A. mali*. They recommended setting a growth chamber's temperature and humidity at 25°C and 70% RH, respectively, for rearing this insect.

Rhopalosiphum rufiabdominalis Sasaki (Homoptera: Aphididae) was cultivated on roots of rice and wheat seedlings. When the aphids matured, they were transferred into glass tubes with the seedlings, and then exposed to *Aphelinus rhopalosiphagus* Yang et Chen. *Aphelinus rhopalosiphagus* was collected from the field in the form of mummified aphids and raised in the laboratory (Chen & Wang 1995; Chen & Huo 1997; Chen & Li 1998). Other facilities and conditions of production of this parasitoid were not mentioned in Chen's studies.

Use of aphid parasitoids

Utilization of *Aphidius gifuensis*

The bionomics, life history, ecology and behavior of *A. gifuensis* have been intensively studied to identify attributes that contributed to its successful biological control of the green peach aphid (Table I). *Myzus persicae* has been controlled in tobacco fields (Zhao et al. 1980; Wu et al. 2000b; Wei et al. 2001) and on vegetables in the greenhouse (Xin 1986). Zhao et al. (1980) recommended using glass containers, where adult parasitoids were collected and fed, for field releases. With this method, in a 55-day period, a total of 120 000 parasitoids were released in a 1.25-ha tobacco field four times at about 9-day intervals. The follow-up field samplings showed that the parasitism rate increased from 0 to 95% and the aphid population decreased from 34.3/plant to 0.1/plant within 60 days. In control fields, the parasitism rate increased from 0.1 to 38.8% and the aphid population increased on average from 33.2/plant to 51.2/plant (maximum 440.5/plant) during the same period. Biological control was even better than chemical controls where pesticides were applied six times (Zhao et al. 1980).

To release *A. gifuensis* in large areas, Wei et al. (2001, 2003) recommended more effective mass rearing and releasing techniques. They found that tobacco plants bearing mummified aphids were the best method to release large quantities of

parasitoids in the field. This method includes hanging tobacco leaves (collected from big glass greenhouses or simple plastic greenhouses) with mummified aphids on plants in the field and introducing small pots of tobacco seedlings (obtained from glass topped greenhouse). Early and large-scale releases of *A. gifuensis* were the best for control of *M. persicae* in tobacco fields. With this technique, a total of 109 800 parasitoids were released in a 3.2-ha tobacco field four times in a 50-day period in 1998; 196 000 parasitoids in 7.6 ha five times in a 55-day period in 1999 (Wu et al. 2000b); 780 000 parasitoids in 20 ha seven times in a 2-month period in 2000 (Wei et al. 2001); 5 600 000 parasitoids in 200 ha in a 2-month period in 2001, and 50 000 000 parasitoids in 2000 ha in nearly a 2.5-month period in 2002 (Wei JN, Wang Y, unpublished data). Five years of releases showed that *A. gifuensis* established widely in treated fields and achieved satisfactory results. For example, in 1999, the percent parasitism of aphids in fields receiving releases of parasitoids were in early, mid, and late season 8.4–52.8, 64–82.3, and 93–93.5%, respectively (Wu et al. 2000b).

Utilization of Aphidius ervi

He et al. (1983) concluded that releasing mummified aphids was better than releasing adult parasitoids, and multiple releases were better than one-time releases. Releasing parasitoids in early spring when aphids first colonized fields was better than later in the season when aphids reached high densities. In the first field, the parasitism rate increased from 0% to an average 56% (47–66%) after 36 000 parasitoids were released three times at 10–15-day intervals. In the second field, the parasitism rate increased from 13.5 to 32% after releasing 121 000 parasitoids once.

Utilization of Lysiphlebus testaceipes

After a detailed laboratory study on the bionomics of *L. testaceipes* imported from the USA, release experiments were carried out in fields and greenhouses from 1983 to 1986 (Zheng & Tang 1989). A total of 21 307, 11 508, 2933 and 19 562 parasitoids were released in cotton, wheat, surrounding fields, and in three greenhouses (ca. 1000 m²) at the Xian Botanical Garden respectively. In 1987, collections from fields and greenhouses revealed that this introduced species had established in greenhouses, but not in the field. Unfortunately, authors did not mention rearing and releasing methods.

Utilization of Aphelinus mali

Field releases of *A. mali* were achieved by releasing adult parasitoids directly or hanging rain-proof paper cartons over apple twigs near the sites of woolly apple aphid colonies. These cartons contained plant leaves with mummified aphids. In 1956, 71 000 parasitoids were released in one orchard. Releases increased parasitism 2.11–7.5 times the control orchard where pesticides were used, and reduced infestation by 21%. During the same period, in two orchards without any pest management measures, infestation rate was over 95% at the end of the season. An investigation in 1957 showed that 19% of trees were infested in orchards where parasitoids were released, while 93% of trees were infested in a control, untreated orchard (Lung et al. 1960).

Conservation of aphid parasitoids

There is no doubt that aphid parasitoids play a very important role in suppressing aphid populations in various communities and ecosystems in agriculture and forest environments (Stary 1970; Liu 1985, 1989a,b; Bao & Gu 1998). There have been many studies on the natural impact of aphid parasitoids in Chinese wheat fields (Zhu et al. 1982; Zong et al. 1986; Zheng et al. 1987; Zhang et al. 1990; Li et al. 1991; Luo et al. 1994; Liu & Li 1999), cotton fields (Shi 1980; Tian et al. 1981; Xi & Zhu 1984; Zheng et al. 1985; Wang & Liu 1989), tobacco fields (Zhao et al. 1980; Xin 1986), and soybean fields (Gao 1994). Most aphid parasitoids are indigenous species that have the potential to suppress aphids in different environments if their populations are conserved (Liu 1985). Furthermore, pesticide applications must be limited through appropriate timing, quantities, and intervals to create a favorable habitat for natural enemies. There is abundant evidence that insecticides used on aphid host plants kill many natural enemies including aphid parasitoids (Stary 1970; Bao & Gu 1998). If pesticide use is a must, then, selective aphicides or bio-aphicides are preferred over broad-spectrum insecticides. Wu et al. (2000b) provided a method of combining insecticides and conserving *A. gifuensis* according to the daily rhythm of this wasp. *Lysiphlebus testaceipes* was introduced and mass released in cotton and wheat fields in Shaanxi Province. But, indigenous aphid parasitoids, *L. japonica*, *L. mirzai*, *T. communis*, *A. gifuensis*, and *Lipolexis gracilis* Förster, were most commonly collected (Zheng & Tang 1989). Recovery of indigenous parasitoids may have resulted from restricting pesticide usage in biological control fields.

Numbers and activity of aphid parasitoids may be promoted in agricultural systems through provision of missing resources such as alternate or supplementary foods and critical habitat needed in reproduction or overwintering (Pickett & Bugg 1998; Landis et al. 2000). However, we have to recognize that biological control of aphids on the cultivated crops alone, does not solve the problem completely. Aphid control in surrounding habitats is also important (Zhang et al. 2000). Other physical and cultural methods are also important for the protection and conservation of aphid parasitoids. These include orchard undergrowth management, shade trees, weeds, intercropping, mixed cropping, strip farming, etc. (Stary 1970; Bao & Gu 1998).

Perspective of aphid parasitoid application in China

Aphids and their parasitoids in China represent a major part of the Oriental and Palearctic fauna. It is estimated that there are over 4000 species of aphids worldwide (Liu 1985) with 736 species in China (Hua 2000). Research on aphids should include their natural enemies. Fundamental studies on aphid parasitoids are insufficient to provide a comprehensive knowledge of aphid parasitoid biology and application. For instance, though there are nearly 400 species of Aphidiidae worldwide and approximately 80 species in Japan, there were only slightly over 40 species recorded in China (Liu 1985), and 99 natural enemy species recorded on the 54 species of aphids in the present paper (Table I). We can presume that there are still large numbers of new species and new records of aphid parasitoids that await discovery in China. Although many aphid parasitoid species have been described, we know little about their host plants and aphid hosts, especially their biology and ecology (Table I). Research on classification, bionomics, life history and ecology of aphid parasitoids is needed to support implementation of aphid biological control.

Although biological control of pests in China has a long history (Chou 1980), large-scale commercial use of natural enemies has not yet started. Much more effort is needed in the commercialization of natural enemies in China. In contrast, the commercialization of biological control has expanded rapidly during the past 30 years in Europe and the USA (Cranshaw et al. 1996; Van Lenteren et al. 1997). Europe has 26 companies and produces more than 80 species of natural enemies (Van Lenteren et al. 1997). North America has 143 companies that sell over 130 species of natural enemies (Hunter 1997; Wan et al. 2000). At present, there are no commercial producers or dealers of natural enemies in China. European companies are profiting from sale of natural enemy products. For example, total sales of natural enemies in Europe amounted to US\$ 15 million (end user value) in 1987 and US\$ 60 million in 1991 (Van Lenteren et al. 1997). In addition, many more species of natural enemies are commercially available in Europe than in the USA, mainly because of the much larger greenhouse industry in Europe. The greenhouse industry in China has been growing rapidly over the past decades (Wei et al. 2001). Therefore, a potential demand for natural enemies could stimulate their commercialization. More attention should be paid to investment in this field and establishment of biological control companies and insectaries in China. Aphid parasitoids have great potential for commercialization in China because they are easy and inexpensive to mass rear and release. The cost of rearing *A. gifuensis* in China is lower (Wei et al. 2001, 2003) than rearing *Aphelinus abdominalis*, *Aphidius colemani*, and *A. ervi* in Europe (Van Lenteren et al. 1997).

Although alternative hosts or even artificial media have been used successfully in the mass culture of host insects, parasitoids or predators (Fleschner 1959), very few successful cases of breeding hymenopterous parasitoids on artificial diet are known (Stary 1970; Thompson 1986). Successful development of parasitoids using *in vitro* technology will require not only a thorough knowledge of the physiology and metabolism of the parasitoids and an understanding of the nature of the parasitoid-host interactions, but also the effect of numerous innate physical and environmental factors on parasitoid growth, development, and survival (Thompson 1986). Mass rearing of aphid parasitoids on artificial diets in China, therefore, is unlikely in the near future, but should not be a limitation to their commercialization. Western countries have already produced and sold natural enemies without the *in vitro* culture technology. Nevertheless, we feel research on artificial diets is justified. Use of such diets is limited simply because of the lack of information on parasitoid physiology and nutrition.

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