Review

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Review

Role of Biological Control in Management of Invasive Exotic Arthropod Pests and Weeds in India

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Simple Summary

Invasive species cause loss of biodiversity, and agricultural productivity, and adversely impact human and environmental health. Biological control of exotic invasive insect pests and weeds has been practiced for more than two centuries in India. It has provided control in the categories of excellent - 16, substantial - 9, and partial - 4 of exotic insect pests and weeds. Further, biological control in association with other components of integrated pest management, has contributed to decline in use of chemical pesticides in the past decade and a half in India, leading to sustainable development and environmental safety.

Abstract

First classical biological control of an exotic invasive weed took place in India in 1795. Thus far, 174 natural enemies have been imported into India and of these, 77 have established in the field. Twelve exotic insect pests and four weeds were successfully controlled with a combination of classical, augmentative, and conservation biological control. Additionally, eight insect pests and one weed were substantially controlled. Augmentative biological control has been adopted as per the needs and availability of resources. Conservation biological control is ubiquitous and it has been facilitated by the adoption of integrated pest management. In the past, biological control activities were sporadic, however, since 1977, Indian Council of Agricultural Research - National Bureau for Agricultural Insect Resouces has been implementing classical biological control regularly in India.

Keywords: biological control; history; successes; invasive insect pests; invasive weeds; India

1. Introduction

Biological invasions pose a serious threat to biodiversity, agricultural productivity, human health and environmental stability and socio-economically it demands heavy investment for management (Ramakrishnan, 1991) [1]. Their socio-economic impact is staggering—India incurred losses between $127.3 billion and 182.6 billion from 1960 to 2020 averaging $2.1 to $3 billion annually. These costs stem from damage to agriculture, forestry, and ecosystems, as well as the expense of managing invasive species (Bang et al., 2022) [2]. Invasive alien species often arrive without their natural enemies, giving them a competitive edge over native species. Despite quarantine regulations, their introduction continues to rise due to globalization, climate change, migration, plant and animal trade, and other factors. Quarantine measures may delay invasions, but they rarely prevent them entirely. Over the past 20 years, India has seen arrival of about 25 economically significant insect pests (Table 1). In management of invasive species, all three strategies of biological control, namely, classical, augmentative, and conservation have been adopted. Classical biological control is a favored frontline strategy for managing invasive species, particularly when their specific and effective natural enemies are present in their native habitats—where these species typically pose no threat. Until 2004,

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166 exotic natural enemies of insect pests and weeds have been imported and studied in India, of these, 71 species have established in the field resulting in six - excellent, seven - substantial, and four - partial control of invasive insect pests and weeds (Singh, 2004) [3]. By 2018, 22 species of natural enemies of weeds have established in the field, of which, seven, four, and nine agents provided excellent, substantial, and partial control, respectively (Sushilkumar and Ray, 2018) [4]. Since 2004, eight exotic natural enemies were imported, of which six established in the field, one did not establish and one yet to be field released. We found either intentionally or fortuitously introduced natural enemies provided 15 - excellent, 9 - substantial and 4 - partial control of invasive insect pests and weeds (Table 2). Augmentative biological control is adopted to suppress pests after they have established by releasing laboratory reared natural enemies. Both introduced and native natural enemies, based on their efficacy in tackling a target insect pest or weed, are utilized in this strategy. Conservation biological control is ubiquitous and it requires judicious, selective use of pesticides (Ehler, 1998) [5] and habitat enhancement (Ferro and NcNeil, 1998) [6]. While management of a few species of invaded insect pests could be soley attributed for conservation biological control, it has been associated in all instances of classical and augmentative biological control (Table 3). Here we present a brief history of biological control actions taken in India over the past two centuries addressing invasive arthropod pests and weeds, natural enemies introduced, local natural enemies involved, augmentative and conservation biological control activities, notable successes and failures, lessons learned, existing gaps in the system, and potential opportunities for future interventions.

Table 1. List of invasive insect pests recorded in the past 20 years.

Sl. No.	Common Name	Scientific Name and Taxonomic Position	Year of First Report
1	Eucalyptus gall wasp	*Leptocybe invasa* (Fisher and LaSalle) (Hymenoptera: Eulophidae)	2006
2	Cotton mealybug	*Phenacoccus solenopsis Tinsley* (Hemiptera: Pseudococcidae)	2006
3	Papaya mealybug	*Paracoccus marginatus* Williams & Granara de Willink (Hemiptera: Pseudococcidae)	2008
4	Madeira mealybug	*Phenacoccus madeirensis* Green (Pseudococcidae: Hemiptera)	2012
5	American Pinhole Borer (on rubber, Areca)	*Eulaptus parallelus* (Fabricius) (Coleoptera: Curculionidae: Platypodinae)	2012
6	Jack Beardsley mealybug	*Pseudococcus jackbeardsleyi* Gimpel and Miller (Pseudococcidae: Hemiptera)	2013
7	South American Tomato Pinworm	*Phthorimaea* (*Tuta*) *absoluta* (Meyrick) (Lepidoptera: Gelechiidae)	2014
8	Coconut Spindle infesting leaf beetle	*Wallacea* sp. (Chrysomelidae: Coleoptera)	2015
9	Western flower thrips	*Frankliniella occidentalis* (Pergande) (Thripidae: Thysanoptera)	2015
10	South East Asian Thrips	*Thrips parvispinus* (Karny) (Thysanoptera: Thripidae)	2015
11	Rugose spiralling whitefly	*Aleurodicus rugioperculatus* Martin (Hemiptera: Aleyrodidae)	2016
12	Legume whitefly	*Tetraleurodes acaciae* (Quaintance) (Hemiptera: Aleyrodidae)	2017
13	Solanum whitefly	*Aleurotrachelus trachoides*(Back) (Hemiptera: Aleyrodidae)	2018
14	Fall armyworm	*Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae)	2018

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15	Bondar's nesting whitefly	*Paraleyrodes bondari* Peracchi (Hemiptera: Aleyrodidae)	2018
16	Neotropical nesting whitefly	*Paraleyrodes minei* Iaccarino (Hemiptera: Aleyrodidae)	2018
17	Woolly whitefly	*Aleurothrixus floccosus* (Maskell) (Hemiptera: Aleyrodidae)	2019
18	Neotropical whitefly	*Aleurotrachelus atratus* Hempel (Hemiptera: Aleyrodidae)	2019
19	Cassava mealybug	*Phenacoccus manihoti* Matile-Ferrero (Hemiptera: Pseudococcidae)	2020
20	Apple leaf blotch miner	*Leucoptera malifoliella* (Costa) (Lyonetiidae: Lepidoptera)	2023
21	Mango soft scale	*Fistulococcus pokfulamensis* Hodgson & Martin (Hemiptera: Coccidae)	2023
22	Walnut leaf miner	*Caloptilia roscipennella* (Hübner) (Lepidoptera: Gracillariidae)	2024
23	Annona Whitefly	*Aleurotrachelus anonae* (Corbett) (Hemiptera: Aleyrodidae)	2024
24	Cactus mealybug	*Hypogeococcus pungens* Granara de Willink (Hemiptera: Pseudococcidae)	2024
25	Nesting Whitefly	*Paraleyrodes pseudonaranjae* Martin (Hemiptera: Aleyrodidae)	2025

Table 2. Invasive species of insects and weeds suppressed by intentionally or fortuitously introduced exotic natural enemies in India.

Number	Excellent	Substantial	Partial
1	*Aleurodicus dispersus* Russell (Hemiptera: Aleyrodidae)	*Aleurotrachelus trachoides*(Back) (Hemiptera: Aleyrodidae)	*Ageratina Adenophora* (Spreng.) King & H. Rob. (Asterales: Asteraceae)
2	*Aleurodicus rugioperculatus* Martin (Hemiptera: Aleyrodidae)	*Aleurothrixus floccosus* (Maskell) (Hemiptera: Aleyrodidae)	*Chromlaena odorata* (L.) R. M.King & H. Rob. (Asterales: Asteraceae)
3	*Heteropsylla cubana* Crawford (Hemiptera: Psyllidae)	*Eriosoma lanigerum* (Hausmann) (Hemiptera: Aphididae)	*Lantana camara* L. (Lamiales: Verbenaceae)
4	*Coccus viridis* (Green) (Hemiptera: Coccidae)	*Parthenium hysterophorus* L. (Asterales: Asteraceae)	*Pontederia crassipes* Mart. (Commelinales: Pontederiaceae)
5	*Comstockaspis perniciosa (Comstock) (Syn:*	*Phenacoccus madeirensis* Green (Pseudococcidae: Hemiptera)	
6	*Icerya purchasi* (Maskell) (Hemiptera: Monophlebidae)	*Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae)	
7	*Leptocybe invasa* (Fisher and LaSalle) (Hymenoptera: Eulophidae)	*Plutella xylostella* (Linnaeus) (Lepidoptera: Plutellidae)	
8	*Paracoccus marginatus* Williams & Granara de Willink (Hemiptera: Pseudococcidae)	*Pseudococcus jackbeardsleyi* Gimpel and Miller (Pseudococcidae: Hemiptera)	
9	*Phenacoccus citri* Risso (Hemiptera: Pseudococcidae)	*Spodoptera frugiperda*(J.E. Smith) (Lepidoptera: Noctuidae)	

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10	*Phenacoccus manihoti* Matile-Ferrero (Hemiptera: Pseudococcidae)
11	*Phenacoccus solenopsisTinsley* (Hemiptera: Pseudococcidae)
12	*Opuntia elatior* Miller (Caryophyllales: Cactaceae)
13	*Opuntia monacantha* Haw. (Caryophyllales: Cactaceae)
14	*Opuntia stricta* (Haw.) (Caryophyllales: Cactaceae)
15	*Salvinia molesta* S.D. Mitchel (Salviniales: Salviniaceae)

Table 3. Invasive insect pests managed by conservation biological control.

S. No	Common Name	Scientific Name and Taxonomic Position
1	Palm infesting whitefly	*Aleurotrachelus atratus* (Hemiptera: Aleyrodidae)
2	Spiralling whitefly	*Aleurodicus dispersus* (Hemiptera: Aleyrodidae)
3	Rugose spiralling whitefly	*Aleurodicus rugioperculatus* (Hemiptera: Aleyrodidae)
4	Solanum whitefly	*Aleurotrachelus trachoides* (Hemiptera: Aleyrodidae)
5	Sugarcane woolly aphid	*Ceratovacuna lanigera* (Hemiptera: Aphididae)
6	Eggplant mealybug	*Coccidohystrix insolita* (Hemiptera: Pseudococcidae)
7	Tortoise scale	*Drepanococcus chiton* (Hemiptera: Coccidae)
8	Banana skipper	*Erionota torus* (Lepidoptera: Hesperiidae)
9	Striped mealybug	*Ferrisia virgata* (Hemiptera: Pseudococcidae)
11	Hibiscus mealybug	*Maconellicoccus hirsutus* (Hemiptera: Pseudococcidae)
12	Spherical mealybug	*Nipaecoccus viridis* (Hemiptera: Pseudococcidae)
13	Bondar's nesting whitefly	*Paraleyrodes bondari* (Hemiptera: Aleyrodidae)
14	Jack Beardsley mealybug	*Pseudococcus jackbeardsleyi* (Hemiptera: Pseudococcidae)
15	Madeira mealybug	*Phenacoccus madeirensis* (Hemiptera: Pseudococcidae)
16	Brown peach aphid	*Pterochloroides persicae* (Hemiptera: Aphididae)
17	South American tomato leafminer	*Phthorimaea absoluta* (Lepidoptera: Gelechiidae)
18	Coffee mealybug	*Planococcus lilacinus* (Hemiptera: Pseudococcidae)
19	Passion vine mealybug	*Planococcus minor* (Hemiptera: Pseudococcidae)
20	Cottony citrus scale	*Chloropulvinaria polygonata* (Hemiptera: Coccidae
21	Green shield scale	*Pulvinaria psidii* (Hemiptera: Coccidae)
22	Long-tailed mealybug	*Pseudococcus longispinus* (Hemiptera: Pseudococcidae)
23	Brown coffee scale	*Saissetia coffeae* (Hemiptera: Coccidae)
24	Fall armyworm	*Spodoptera frugiperda* (Lepidoptera: Noctuidae)

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25	Legume feeding whitefly	*Tetraleurodes acacia* (Hemiptera: Aleyrodidae)
26	Araucaria mealybug	*Uhleria (Eriococcus) araucariae* (Hemiptera: Eriococcidae)

Classical biological control of invasive species has a long history in India. In 1795, control of the common prickly pear *Opuntia monocantha* (Wildenow) Haworth (Cactaceae) with the introduction of the cochineal insect *Dactylopius ceylonicus* (Green) (Hemiptera: Dactylopiidae), which was intended for production of cochineal dye, was serendipitously recognized. This was the first documented record of biological control of an alien invasive plant in the world (Zimmermann et al., 2009) [7]. Based on this achievement, the agent was formally shipped from India to Sri Lanka for biological control of *O. monocantha* in 1865 resulting in the first documented intentional transfer of an agent for classical biological control (Goeden, 1988) [8]. In the early 1900s, recognizing seriousness of invasive weeds, Government of India deputed Mr. Ramachandra Rao from November 15, 1916 to March 31, 1919 to study the distribution and natural enemies of lantana, *Lantana camara* L. (Verbanaceae) throughout India and Myanmar (Ramachandra Rao, 1920) [9]. He reported 148 local herbivores including two fortuitously introduced ones. Subsequently, lantana pod fly, *Ophiomyia lantanae* (Froggatt) (Diptera: Agromyzidae) from Hawaii was introduced in 1921 (Subramanyam, 1934) [10]. In 1926, another cochineal insect *Dactylopius opuntiae* (Cockerell) (Hemiptera: Dactylopiidae) was introduced to India from Sri Lanka for control of erect prickly pear *Opuntia stricta* (Haworth) and red-flower prickly pear *Opuntia elatior* Miller (Cactaceae) (Kunhikannan, 1928) [11]. Afterwards biological control of invasive weeds was carried out sporadically (Muniappan, 2018) [12] by the forestry department, Commonwealth Institute of Biological control (CIBC) (now, Center for Agriculture and Biosciences International (CABI)) station in India and institutions of Indian Council of Agricultural Research (ICAR). However, relatively little work has been done on new introductions of bioagents against weeds after 1980s (Sushilkumar et al., 2024) [13].

Biological control of invasive insect pests in India started when coffee green scale *Coccus viridis* Green (Hemiptera: Coccidae) was accidentally introduced to southern India in the 1890s. In 1898, Mr. Howard O. Newport, a planter and an amateur entomologist from Lower Pulneys, Madurai district in southern India introduced *Cryptolaemus montrouzieri* Mulsant (Coleoptera: Coccinellidae) from Australia with the support of United Planters' Association of Southern India and the Government of Madras (Mayne, 1953) [14] in an attempt to control *C. viridis*. In addition to the targeted pest, it has proven to be an effective agent for controlling mealybugs and soft scales (Singh, 2004; Ballal, 2022) [3,15]. In 1929, for control of cottony cushion scale *Icerya purchasi* Maskell (Hemiptera: Monophlebidae), the lady beetle *Novius* (*Rodolia*) *cardinalis* (Mulsant) (Coleoptera: Coccinellidae) of Australian origin from South Africa was introduced (Rao et al., 1971) [16]. The parasitoid, *Aphelinus mali* (Haldimann) (Hymenoptera: Aphelinidae) was introduced from England in 1930 for control of woolly apple aphid, *Eriosoma lanigerum* (Hausmann) (Hemiptera: Aphididae) (Singh, 1989) [17]. Two parasitoids, *Bracon gelechiae* (Ashm.) (Hymenoptera: Braconidae) and *Trichogramma australicum* Gir. (Hymenoptera: Trichogrammatidae) were introduced in 1944 and 1948, respectively, for control of potato tuber moth, *Phthorimaea operculella* Zeller (Lepidoptera: Gelechiidae) (Rao et al., 1971) [16]. From 1957 to 1987, CIBC sub-station carried out classical biological control research activities in India and in 1977 All India Coordinated Research Project on Biological Control of Crop Pests and Weeds was started which eventually morphed into ICAR-National Bureau of Agricultural Insect Resources (NBAIR) to carry out biological control programs. As of 2022, there are 361 biological control laboratories in India consisting of 35 Central Integrated Pest Management Centers (CIPMCs) and 38 State Biological Control Laboratories (SBCLs) of Directorate of Plant Protection, Quarantine and Storage (DPPQS), 49 Indian Council of Agricultural Research Laboratories, 98 State Agricultural University Laboratories and 141 private laboratories (Mathew and Singh, 2022) [18].

2. Status of Biological Control

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2.1. Invasive Arthropod Pests of India

Exotic arthropods and weeds introduced to India are presented below in a chronological order of their introduction, with a brief review of exotic natural enemies introduced for their control, and local natural enemies recruited by them.

Woolly apple aphid, *Eriosoma lanigerum* a native of China was accidentally introduced to India in 1889. It infests members of the family Rosaceae, with apple being the preferred host. An exotic parasitoid, *Aphelinus mali* was introduced from England in 1930 (Singh, 1989) [17]. Local natural enemies of this aphid recorded in India were *Coccinella septempunctata* L., *Coccinella transversoguttata* Faldermann, *Priscibrumus uropygialis* (Mulsant), *Harmonia dimidiata* (L.), *Chilocorus infernalis* Mulsant, *Adalia tetraspilota* (Hope), *Hippodamia variegata* (Goeze), *Oenopia conglobata* L., (Coleoptera: Coccinellidae), *Syrphus* spp. (Dipitera: Syrphidae), and *Chrysoperla zastrowi sillemi* (Esben-Petersons), *Chrysopa nigricornis* Burmeister, (Neuroptera: Chrysopidae) (Asante, 1997, Rasool et al., 2019, Singh et al., 2020) [19–21].

Coffee green scale, *Coccus viridis* is believed to be a native of Brazil and it was introduced to southern India in the 1890s. It is a polyphagous pest affecting coffee, avocado, citrus, tea, mango, cassava, guava and others. To control this pest, Mr. Howard O. Newport introduced *C. montrouzieri* in 1898 from Australia (Mayne, 1953) [14]. No follow up work was taken up as Mr. Newport left India in 1899, however, in 1951, Puttarudriah et al. (1952) [22] found larvae and pupae of *C. montrouzieri* on the trunks of *Araucaria* pines around Bengaluru. Later, they also found *C. montrouzieri* specimens in the collections of Mysore State Entomology Division that were taken in 1940 on mealybugs in Bengaluru. Local parasitoids observed on *C. viridis* were *Coccophagus ceroplastae* (Howard), *C. cowperi* Girault, and *Coccophagus* sp. (Hymenoptera: Aphilinidae), *Anicetus annulatus* Timberlake, and *Encyrtus lecaniorum* (Mayr), *Metaphycus helvolus* (Compere), *M. lichtensiae* (Howard), *M. maculatus* Agarwal (Hymenoptera: Encyrtidae) (Srinivasa, 1987) [23].

San Jose scale, *Comstockaspis* (=*Quadraspidiotus*) *perniciosa* (Comstock) (Hemiptera: Diaspididae) is a native of northern China and North Korea (Singh 2004) [3]. It appeared in India in 1910, possibly introduced along with the Japanese ornamental plant *Chaenomeles* (*Cydonia*) *japonica* (Thunb.) (Rosaceae) (Fotidar, 1941) [24]. It is a pest of deciduous fruit trees. Exotic natural enemies introduced were *Aphytis diaspidis* Howard from USA in 1960, *Aphytis* sp. nr. *diaspidis* How. (Hymenoptera: Aphelinidae) from Japan via USA in 1966, and *Encarsia perniciosi* (Tower) (Hymenoptera: Eulophidae) California strain from USA in 1958 and 1959, Chinese and Illinois strains via Switzerland in 1960, and Russian strain via France in 1960 (Sankaran, 1974) [25]. Additionally, *Chilochorus kuwane* Silv. (Coleoptera: Coccinellidae) (origin Japan) and *Cybocephalus gibbulus* Erickson (origin Japan) (Coleoptera: Cybocephalidae) were imported from CIBC station In Trinidad (Rao et al., 1971) [16]. Of the two introduced parasitoids, only *E. perniciosi* was recovered from the field. However, *Aphytis* sp. *proclia* group was recorded from field surveys (Gupta, 2005) [26]. Local natural enemies, *Chilocorus circumdatus Gyllenhal, C. infernalis*, *C. septempunctata*, *Sticholotis marginalis* Crotch *(Coleoptera: Coccinellidae), Aphytis lingnanensis* Compere, *Aphytis paramaculicornis* DeBach & Rosen (Hymenoptera: Aphelinidae), and *Azotus kashmirensis* Narayanan (Hymenoptera: Azotidae) were *reported on this pest from India (Gupta, 2005) [26]. Singh (2004) [3]and Gupta (2005) [26] recommended inoculative release of the parasitoids E. perniciosi, and A. sp. proclia group and the coccinellid C. infernalis in the beginning of the spring season for control of this pest.*

Red banded mango caterpillar, *Deanolis sublimbalis* Snellen (Lepidoptera: Crambidae) is of South and Southeast Asia in origin. It was reported from Darjeeling and Sikkim in 1903, Kolkata in 1945, and Andhra Pradesh in 1993 (Zaheruddeen and Sujatha, 1993) [27]. No natural enemies were recorded in India, however, egg parasitoids, *Trichogramma chilonis* and *Trichogramma chilotraeae* (Hymenoptera: Trichogrammatidae) have been recorded in the Philippines (Jackson, 2013) [28].

Potato tuber moth, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae) a native of Andes, South America was introduced to East Bengal, India (now Bangladesh) in 1906 on potato seed, imported from Italy (Lefroy, 1907, Chandel et al., 2020) [29,30]. It is a major pest of potato in the field and storage. A parasitoid *Bracon gelechiae* (Ashm.) (Hymenoptera: Braconidae) was imported from

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Canada in 1944. In 1948, *T. australicum* (Hymenoptera: Trichogrammatidae) (origin: not known) was released in Nanjangud, Karnataka and Coonoor, Tamil Nadu (Rao et al., 1971) [16]. In 1964 and 1965, five species of larval parasitoids, namely, *Agathis unicolor* (Schr.), *Apanteles scutellaris* Mues., *Orgilus lepidus* Muesebeck (Hymenoptera: Braconidae), *Campoplex haywardi* Blanch. and *Temelucha* sp. (Hymenoptera: Ichneumonidae) and the egg-larval parasitoid, *Copidosoma uruguayensis* Tach. (Hymenoptera: Encyrtidae) from South America and the larval parasitoid *Apanteles subandinus* Blanchard (Hymenoptera: Braconidae) from North America were introduced from the California station of CIBC (Rao et al., 1971) [16]. Additional parasitoids *Orgilus parcus* Turner (Hymenoptera: Braconidae), and *Diadegma stellenboschense* Cameron from South Africa and *Diadegma raoi* Gupta (Hymenoptera: Ichneumonidae) from Cyprus were also introduced (year not known) (Rao et al., 1971) [16]. In 1968, *Diadegma turcator* Aubert (Hymenoptera: Ichneumonidae) from Cyprus was introduced (Sankaran 1974) [25]. *Chelonus kellieae* Marsh (Hymenoptera: Braconidae) from Costa Rica in 1978, *Copidosoma koehleri* Blanchard (Hymenoptera: Braconidae) from Australia in 1976, and *Copidosoma desantis* Annecke and Mynhardt (Hymenoptera: Encyrtidae) from Peru were introduced (Singh, 1994) [31]. The parasitoid, *Chelonus blackburni* Cameron (Hymenoptera: Braconidae) was introduced from USA in 1976 by CIBC India (Nagarkatti and Singh, 1989) [32]. A local parasitoid, *T. chilonis* and the introduced parasitoid *C. blackburni* are used in augmentative releases for control of *P. operculella*.

Diamondback moth, *Plutella xylostella* L. (Lepidoptera: Plutellidae), a native of either Europe or South Africa which has established all over the world, is a pest of cruciferous crops. It was first reported from India in 1914 (Fletcher, 1914) [33]. The parasitoid, *Diadegma semiclausum* (Hellén) (Hymenoptera: Ichneumonidae) was introduced to India from Taiwan in 1994. Egg parasitoids, *Trichogrammatoidea bactrae* Nagaraja was introduced from Taiwan in 1992 (Singh, 2004) [3] and *Trichogramma brassicae* Bezdenko (Hymenoptera: Trichogrammatidae) was introduced from Canada in 2005 (Jalali, 2013) [34]. Exotic parasitoids introduced for other pests, *Trichogramma evanescens* Westwood, *Trichogramma brasiliensis* (Ashmead) and *Trichogramma pretiosum* Riley (Hymenoptera: Trichogrammatidae) were reported to parasitize *P. xylostella* in India. According to Singh (1994) [31], out of 39 species of natural enemies recorded on *P. xylostella*, *Cotesia vestalis* (Holiday) (Hymenoptera: Braconidae), *Oomyzus sokolowskii* Kurdjumov (Hymenoptera: Eulophidae) *Diadromus collaris* (Gravenhorst) and *D. semiclausum* (Hymenoptera: Ichneumonidae) are the key parasitoids.

Lantana bug, Kew bug (*Insignorthezia insignis* (Browne)) (Hemiptera: Ortheziidae), a native of neotropics introduced by accident to Nilgris, southern India from Sri Lanka in 1915 (Ramachandra Rao, 1920) [9]. It is a pest of coffee, citrus and several other fruit and vegetable crops and also found to colonize on weeds like *Lantana camara* L., *Chromolaena odorata* (L.) King and Robinson, *Mikania micrantha* Kunth (Asteraceae) and others. The coccinellid beetle, *C. montrouzieri* has been reported to feed on this pest (Singh, 2004) [3]. The release of *Hyperaspis pantherina* Fürsch (Coleoptera: Coccinellidae) in St. Helena, Hawaii, four African countries and Peru has given substantial control of *I. insignis* (Booth et al., 1995, Fowler, 2004) [35,36].

Chinese Citrus Fly, *Bactrocera minax* (Enderlein) (Diptera: Tephritidae) is a pest of citrus fruits, originated from the temperate southern Yunnan-Guizhou plateau in China (Xia et al., 2018) [37]. The Chinese citrus fly was for the first time described in 1920 based on the specimens collected from Sikkim, India by Enderlein and named *Polistomimetes minax* (Thompson, 1998) [38]. Its distribution is still limited to Sikkim and northern part of West Bengal in India. Chinese citrus fly is not attracted to methyl eugenol or cue-lure. Monitoring has to be done with protein baits or fruit mimicking traps (Rashid et al., 2021) [39]. No natural enemies have been reported of this pest from India. Only one parasitoid, *Diachasmimorpha feijeni* van Achterberg (Hymenoptera: Braconidae) has been reported from Bhutan (van Achterberg, 1999) [40].

Cottony cushion scale, *Icerya purchasi* Maskell (Hemiptera: Monophlebidae), a native of Australia was introduced to India in 1928 via Sri Lanka (Ramachandra Rao and Cherian, 1944) [41]. It is a polyphagous pest of woody plants, notably the genus *Citrus*. The lady beetle, *Novius* (*Rodolia*) *cardinalis* Mulsant (Coleoptera: Coccinellidae) was introduced in 1930 (origin Australia) by receiving

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one consignment from South Africa, and a second one from California through Commonwealth Institute of Entomology and a third one from Egypt. Shipments of the parasitoid *Cryptochetum iceryae* (Williston) (Diptera: Cryptochetidae) were received from California (origin Australia) in 1947 and 1948 and its field release did not result in establishment (Rao et al., 1971) [16]. Local natural enemies found attacking *I. purchasi* were *Novius* (*Rodolia*) *fumidus* (Mulsant) (Coleoptera: Coccinellidae) (Patel et al., 2022) [42], and *Stathmopoda melanochra* Meyr. (Lepidoptera: *Stathmopodidae*) (Ramachandra Rao and Cherian, 1944) [41].

Codling moth, *Laspeyresia* (*Cydia*) *pomonella* (L.) (Lepidoptera: Tortricidae), a native of Europe and Northwestern Asia, was introduced to Ladakh area of India in 1972 from north western border of Pakistan and Afghanistan (Malik et al., 1972; Opinion and Editorial, 2018) [43,44]. It is a serious pest of apple, pear, apricot, and walnut and it is still confined to the union territory Ladakh. Egg parasitoid *Trichogramma embyrophagum* (Hartig) (Hymenoptera: Trichogrammatidae) was introduced from Germany and France in 1993 and 2007, respectively (Jalali, 2013) [34]. Egg parasitoids introduced for other pests *T. evanescens T. pretiosum* (Kaushik and Arora., 1998) [45], and *Trichogramma cacoeciae* Marchal (Hymenoptera: Trichogrammatidae) (Opinion and Editorial, 2018) [44] have also been reported to parasitize this pest.

Brown peach aphid, *Pterochloroides persicae* (Cholodkovsky) (Hemiptera: Aphididae) a native of China, established in the state of Punjab and the union territory Kashmir in 1970 (Bindra and Bakhetia, 1970) [46]. Local natural enemies recorded were *Harmonia eucharis* (Mulsant), *C. septempunctata*, *H. variegata*, *Oenopia conglobata* (L.), *Priscibrumus uropygialis* (Mulsant), and *A. tetraspilota* (Coleoptera: Coccinellidae), and *C. zastrowi sillemi* (Neuroptera: Chrysopidae) (Mahendiran et al., 2018) [47].

Citrus mealybug, *Planococcus citri* (Risso) (Hemiptera: Pseudoccocidae) is Asiatic in origin but pantropical in distribution and also found in some sub-tropical regions. It was reported from India in 1987 (Mani and Thontadarya, 1987) [48]. A parasitoid, *Leptomastrix dactylopii* (Hymenoptera: Encyrtidae) of Brazilian origin was introduced to India from Trinidad in 1983 (Singh, 2004) [3]. An indigenous parasitoid *Coccidoxenoides peregrinus* (Timberlake) (Hymenoptera: Encyrtidae), along with the introduced coccinellid *C. montrouzieri* were found attacking this mealybug.

Leucaena psyllid, *Heteropsylla cubana* (Crawford) (Hemiptera: Psyllidae) is a native of Central America introduced to India from Sri Lanka in 1988 (Gopalan et al., 1988) [49]. It is a pest of *Leucaena leucocephala* (Lam.) de Wit (Fabaceae); some consider it as an invasive plant and others consider it as a beneficial fodder plant. Soon after finding *H. cubana* in India, *Curinus coeruleus* (Mulsant) (Coleoptera: Coccinellidae) (originated from Mexico) was introduced from Thailand in 1988 (Jalali and Singh, 1989) [50]. Native predators, *Cheilomenes sexmaculata* (Fabricius) (Coleoptera: Coccinellidae), and *Pantala flavescens* (Odonata: Libellulidae) also reported to feed on this psyllid (Rajagopal et al., 1990) [51].

American serpentine leafminer, *Liriomyza trifolii* (Burgess) (Diptera: Agromyzidae), a native of the eastern part of the USA was introduced to India in 1990 (Viraktamath et al., 1993) [52]. The parasitoid, *Diglyphus begini* (Ashmead) (Hymenoptera: Eulophidae) was introduced to India from California but it did not establish (Viraktamath, 2002) [53]. Local parasitoids *Hemiptarsenus varicornis* (Girault) and *Chrysonotomyia rexia* Narendran, Galande & Mote (Hymenoptera: Eulophidae) have been reported on *L. trifolii* in India (Durairaj, 2007) [54].

Coffee berry borer, *Hypothenemus hampei* (Ferrari) (Coleoptera: Curculionidae) is a native of West Africa introduced to India from Sri Lanka in 1990 (Kumar et al., 1990) [55]. Two parasitoids, *Cephalonomia stephanoderis* Betrem and *Prorops nasuta* Waterston (Hymenoptera: Bethylidae) were imported from Mexico in 1995. *Phymastichus coffea* LaSalle (Hymenoptera: Eulopidae) and *P. nasuta* were imported from Colombia in 1999 (Central Coffee Research Institute, 2002) [56]. Efficacy of these introduced parasitoids is yet to be evaluated.

Mango Fruit Borer, *Citripestis eutraphera* (Meyrick) (Lepidoptera: Pyralidae) is a native of Java, Indonesia that reached Andaman Islands in 1991 and south India in 2014 (Jayanthi et al., 2014) [57]. No natural enemies were recorded on it from India yet.

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Spiralling whitefly, *Aleurodicus dispersus* Russell (Hemiptera: Aleyrodidae), a native of Central America and the Caribbean region was reported from India in 1994 (David and Regu, 1995) [58]. Fortuitously introduced parasitoids reported on it are *Encarsia guadeloupae* Viggiani (Hymenoptera: Aphelinidae), *Encarsia* (?) *haitiensis* Dozier, and *Encarsia dispersa* Polaszek (Hymenoptera: Aphelinidae). Viraktamath (2002) [53] and Mani and Krishnamoorthy (2002) [59] reported native predators *Axinoscymnus puttarudriahi* Kapur, *C. sexmaculata*, *Chilocorus nigrita* (Fabricius), *C. montrouzieri*, *Pseudoaspidimerus trinotatus* (Thunberg), *Serangium parcesetosum* Sicard, *Scymnus nubilus* Mulsant (Coleoptera: Coccinellidae), *Cybocephalus* sp. (Coleoptera: Cybocephalidae), *Acletoxenus indicus* Malloch (Diptera: Drosophilidae), *Apertochrysa astur* (Banks), *Mallada boninensis* (Okamoto), *C. zastrowi sillemi*, (Neuroptera: Chrysopidae), and *Notiobiella* sp. (Neuroptera: Hemerobiidae).

Coconut eriophyid mite, *Aceria guerreronis* Keifer (Acarina: Eriophyidae) is a native of Central and South America and it was first described from the specimens collected in Mexico. In India it was first reported from Ernakulam, Kerala in 1997 (Sathiamma et al., 1998) [60]. The fungus *Hirsutella thomsonii* Fisher (Hypocreales: Ophiocordycipitaceae) has been reported to infect this mite in the fields (SreeramaKumar et al., 2001) [61].

Eucalyptus gall wasp, *Leptocybe invasa* Fisher & LaSalle (Hymenoptera: Eulophidae) is a native of Australia that invaded Villuppuram district of Tamil Nadu, India in 2001 (Yousuf et al., 2017) [62]. The parasitoid *Quadrastichus mendeli* Kim & La Salle (Hymenoptera: Eulophidae) was imported from Israel in 2008 and field released in 2010 in various parts of India. Also, local parasitoids *Megastigmus viggianii* Narendran and Sureshan, *Megastigmus dharwadicus* (Narendran, Girish Kumar, and Vastrad) (Hymenoptera: Megastigmidae), and *Aprostocetus gala* Walker (Hymenoptera: Eulophidae) were recorded from Karnataka (Yousuf et al., 2017; Ramanagouda et al., 2011; Shylesha, 2008; Shylesha et al., 2018) [62–65].

Sugarcane woolly aphid, *Ceratovacuna lanigera* (Zehntner) (Hemiptera: Aphididae), a native of Southeast Asia, established in West Bengal in 1958 and later in north-east India (Basu and Banerjee, 1958) [66]. It invaded western India starting with Maharashtra in 2002, and subsequently reached southern India (Baitha et al., 2019) [67]. In 2004, *Encarsia flavoscutellum* Zehntner (Hymenoptera: Aphelinidae) *was collected from Assam and released in Karnataka and other south Indian states.* Local predators *Dipha aphidivora* (Meyrick) (Lepidoptera: Pyralidae) and *Micromus igorotus* (Banks) (Neuroptera: Hemerobiidae) and *Eupeodes confrater* Weidemann (Diptera: Syrphidae) were also recorded (Srikanth et al., 2015) [68].

Erythrina gall wasp, *Quadrastichus erythrinae* Kim (Hymenoptera: Eulophidae) is a native of Africa. Tanzania is the putative source of the population that invaded Asia and the Pacific. It invaded Kerala, India in 2005 causing galls on leaves and tender stems of *Erythrina stricta* Roxb, (Fabaceae) (Faizal et al., 2006) [69]. In India, a species of *Aprostocetus*, previously misidentified as *Aprostocetus gala* Walker (Hymenoptera: Eulophidae), has been recorded as a potential parasitoid of the erythrina gall wasp. This species is closely related to *A. felix* La Salle, Yang and Lin, which was described from Taiwan as a parasitoid of this pest. Further investigations, including molecular characterization, are required to confirm the taxonomic identity of the species from India (ICAR-NBAIR Featured Insects Database https://databases.nbair.res.in/Featured_insects/Aprostocetus.php). Meanwhile the parasitoid, *Eurytoma erythrinae* Gates and Delvare (Hymenoptera: Eurytomidae) was successfully introduced in Hawaii, where it has provided effective control of the erythrina gall wasp (Kaufman et al., 2020) [70]. Considering its host specificity and proven effectiveness, India may consider introducing this parasitoid if the erythrina gall wasp problem persits.

Cotton mealybug, *Phenacoccus solenopsis* Tinsley (Hemiptera: Pseudococcidae) is a native of USA and it reached Punjab, India in 2006 (Suresh and Kavitha, 2008) [71] via Pakistan. It is a serious pest of cotton but it has been reported on over 200 host plants. A parasitoid *Aenasius arizonensis* (Girault) (Hymenoptera: Encyrtidae) from the native region of this mealybug was fortuitously introduced to India in 2009 which provided effective control of this pest (Ram and Saini, 2010) [72]. Local natural enemies recorded on this mealybug are *Hyperaspis maindroni* Sicard, *Brumoides suturalis* (Fabricius), *C. sexmaculata*, *C. septempunctata*, *H. variegata*, *Nephus regularis* Sicard, *Scymnus coccivora* Ayyar, *C.*

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montrouzieri (Coleoptera: Coccinellidae), *C. zastrowi sillemi*, *Mallada* sp., (Neuroptera: Chrysopidae), *Encyrtus aurantii* (Geoffroy), *Anagyrus mirzai* Agarwal and Alam, *Anagyrus kamali* Moursi, *Anagyrus dactylopii* (Howard), *Homalotylus albiclavatus* (Agarwal), *Metaphycus* sp., (Hymenoptera: Encyrtidae), *Aprostocetus bangaloricus* Narendran (Hymenoptera: Eulophidae), *Chartocerus kerrichi* (Agarwal) (Hymenoptera: Signiphoridae), *Pachyneuron leucopiscida* Mani (Hymenoptera: Pteromalidae) (Ram and Saini, 2010; Fand and Suroshe, 2015) [72,73].

Papaya mealybug, *Paracoccus marginatus* Williams and Granara de Willink (Hemiptera: Pseudococcidae) is a native of Mexico accidentally introduced to India in 2008 (Muniappan et al., 2008) [74]. It is a pest of papaya, mulberry, cassava and several other crops. Three parasitoids from Puerto Rico of Mexican origin, *Acerophagus papayae* Noyes and Schauff, *Anagyrus loeckei* Noyes and Menezes, and *Pseudleptmastix mexicana* Noyes and Schauff (Hymenoptera: Encyrtidae), were introduced in 2010, of which *A. papayae* proved to be effective in suppressing this pest. Local predators *Spalgis epius* (Westwood) (Lepidoptera: Lycaenidae) *C. montrouzieri*, *Scymnus coccivora* Ramakrishna Ayyar, *Nephus regularis* (Sicard), and *Slipinskiscymnus saciformis* (Motschulsky) (Coleoptera: Coccinellidae), *Gitonides* sp. (Diptera: Drosophilidae), and Chrysopid sp. (Neuroptera: Chrysopidae) were reported on this pest (Poorani et al., 2024) [75].

Jack Beardsley mealybug, *Pseudococcus jackbeardsleyi* Gimpel and Miller (Hemiptera: Pseudococcidae) is a native of the neotropics recorded in Tamil Nadu, India in 2012 (Mani et al., 2013) [76]. It is a polyphagous pest of many fruit, vegetable and ornamental crops. *C. montrouzieri*, *Mallada boninensis* (Okamoto) (Neuroptera: Chrysopidae), *S. epius* (Lepidoptera: Lycaenidae) have been reported to be effective in controlling this mealy bug negating the need for classical biological control (Mani and Shylesha, 2021) [77]. In Tamil Nadu, *P. jackbeardsleyi* was prominent among mealybug populations, posing a significant threat to banana production. Several coccinellid predators were identified as natural enemies attacking this mealybug, including *S. coccivora*, *N. regularis*, and *S. saciformis*. A new species, *Scymnus spicatus* was also described as a predator of *P. jackbeardsleyi* (Poorani et al., 2024) [75].

Madeira mealybug, *Phenacoccus madeirensis* Green (Hemiptera: Pseudococcidae) is a native of neotropics introduced to India in 2012 (Shylesha and Joshi, 2012) [78]. It is a polyphagous pest attacking many ornamental and fruit crops and weeds. Native and naturalized natural enemies recorded were *Nephus regularis* (Sicard) (Nandudkar et al., 2025) [79], *C. montrouzieri*, *C. sexmaculata*, *Scymnus* sp., *Jauravia* sp. *Novius* (*Rodalia*) sp. *Chilocorus* sp. *Nephus regualris* Sicard (Coleoptera: Coccinellidae), *S. epius* (Lepidoptera: Lycaenidae), *C. zastrowi sillemi* (Neuroptera: Chrysopidae), *Cacoxenus* (*Gitonides*) *perspicax* (Knab) (Diptera: Drosophilidae), *Diadiplosis* sp. (Diptera: Cecidomyiidae), (Lepakshi, 2015) [80], *Allotropa* sp., (Hymenoptera: Platygastridae), *Anagyrus amnestos* Rameshkumar, Noyes, Poorani & Chong, *Anagyrus qadrii* (Hayat, Alam & Agarwal), *A. loecki* and *Anagyrus* sp. nov. nr. *sinope* Noyes and Menezes (Hymenoptera: Encyrtidae) (Mani and Shylesha, 2021) [77].

Banana skipper, *Erionota torus* Evans (Lepidoptera: Hesperiidae) is a native of Southeast Asia. It invaded southern India in 2012. Egg parasitoids *Ooencytus pallidipes* (Ashmead) (Hymenoptera: Encyrtidae), *Agiommatus* sp. (Hymenoptera: Pteromalidae), *Anastatus* sp. (Hymenoptera: Eupelmidae), and *Telenomus* sp. (Hymenoptera: Scelionidae); larval parasitoids *Elasmus brevicornis* Gahan (Hymenoptera: Eulophidae), *Pediobius* sp. nr. *elasmi* (Ashmead) (Hymenoptera: Eulophidae), *Tetrastichus* sp. (Hymenoptera: Eulophidae), *Acropimpla* sp. nr. *nigroscutis* (Cameron) (Hymenoptera: Ichneumonidae), *Cotesia* sp. (Hymenoptera: Braconidae); and the pupal parasitoids *Senometopia* sp., *Winthemia sumatrana* (Townsend), and *Drino* (*Palexorista*) sp., (Diptera: Tachinidae), *Megaselia scalaris* (Loew) (Diptera: Phoridae); and pupal parasitoids *Brachymeria lasus* (Walker) (Hymenoptera: Chalcididae) and an unidentified species of Tachinidae were reported from southern India (Poorani et al., 2020; Abdul-Jaleel et al., 2024) [81,82].

South American tomato leafminer, *Phthorimaea* (=*Tuta*) *absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is a native of South America that reached Pune, India in 2014 (Sridhar et al., 2014) [83]. Native and naturalized natural enemies of this leafminer recorded were *Nesidiocoris tenuis* (Reuter)

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(Hemiptera: Miridae), *Trichogramma achaeae* Nagaraja and Nagarkatti, *Trichogramma pretiosum* Riley and *T. bactrae* (Hymenoptera: Trichogrammatidae), *Neochrysocharis formosa* (Westwood) (Hymenoptera: Eulophidae), *Habrobracon* sp. (Hymenoptera: Braconidae) and *Goniozus* sp. (Hymenoptera: Bethylidae) (Ballal et al., 2016) [84].

Solanum whitefly, *Aleurotrachelus* (=*Aleurothrixus*) *trachoides* (Back) (Hemiptera: Aleyrodidae) is of neotropical origin and a pest of Solanaceae, Verbenaceae, and Convolvulaceae plants and it was introduced to India in 2014 (Dubey and Sundararaj, 2015) [85]. It is a vector of begomovius and transmits Duranta leaf curl virus in tomato, bell pepper and potato crops (Chandrashekar et al., 2020) [86].. Fortuitously introduced parasitoid *Encarsia cubensis* Gahan (Hymenoptera: Aphelinidae) has been recorded on this whitefly (Yadav et al., 2025) [87].

Tobacco thrips, *Thrips parvispinus* (Karny) (Thysanoptera: Thripidae), a native of southeast Asia, reached India in 2015 (Tyagi et al., 2015) [88]. It is polyphagous but causes serious damage to pepper and other crops. A natural enemy *Menochilus sexmaculatus* (Fabricius) (Coleoptera: Coccinellidae) has been recorded (Thorat et al., 2022) [89].

Western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), a native to western North America, was first recorded in Karnataka, India, in 2015, infesting tomato crops (Tyagi and Kumar, 2015) [90]. This pest has also been reported on flower crops grown under both open and protected cultivation in the Nilgiris and Salem districts of Tamil Nadu, India (Suganthy et al., 2015) [91]. No natural enemies of this thrips have been recorded in India.

Rugose spiralling whitefly, *Aleurodicus rugioperculatus* Martin (Hemiptera: Aleyrodidae) is a native of Central America that invaded southern India in 2016 (Sundararaj and Selvaraj, 2017) [92]. The fortuitously introduced parasitoids *E. dispersa* and *Encarsia guadeloupe* Viggiani (Hymenoptera: Aphelinidae) were found parasitizing this pest. Local predators observed on this pest were *A. astur*, (Neuroptera: Chrysopidae), *Cybocephalus* sp. (Coleoptera: Cybocephalidae), *Diadiplosis* sp. (Diptera: Cecidomyiidae), *Jauravia pallidula* Motschulsky, *C. sexmaculata*, and *Stethorus* sp. (Coleoptera: Coccinellidae) (Poorani and Thanigairaj, 2017) [93].

Legume feeding whitefly, *Tetraleurodes acaciae* (Quaintance) (Hemiptera: Aleyrodidae) is a native of neotropics reported from India in 2017 (Sundararaj and Vimala, 2018) [94]. It was first recorded on *Leucaena leucocephala* and prefers to feed on plants belonging to family Fabaceae. No parasitoids have been recorded on this pest in India.

Bondar's nesting whitefly, *Paraleyrodes bondari* Peracchi (Hemiptera: Aleyrodidae), of neotropical origin, was reported from India in 2018 (Josephrajkumar et al., 2019) [95]. No parasitoids were reported on this whitefly in India (Sadhana et al., 2023) [96] Predators *Cybocephalus indicus* Tian and Ramani, *Cybocephalus nipponicus* Endrödy-Younga (Coleoptera: Cybocephalidae) and *Delphastus catalinae* (Horn) (Coleoptera: Coccinellidae) were reported feeding on it (Sadhana et al., 2022) [97].

Fall armyworm, *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae), a native of the Americas, was introduced to India in 2018 via Africa. Even though it is a polyphagous pest, the population that reached India preferred maize the most. A parasitoid *Telenomus remus* Nixon (Hymenoptera: Scelionidae) introduced from Papua New Guinea to India in 1963 (Rao et al., 1971) [16] for control of *Spodoptera litura* (Fabricius) (Lepidoptera: Noctuidae) and *Achaea janata* (L.) (Lepidoptera: Erebidae) has become a major natural enemy of *S. fugiperda,* supporting the theory of 'New Association' proposed by Hokkanen and Pimentel (1984) [98]. In addition, local parasitoids include: *Trichogramma chilonis* (Ishii) (Hymenoptera: Trichogrammatidae), *Chelonus* nr. *blackburni* (Cameron), *Chelonus formosanus* Sonan (Hymenoptera: Braconidae), *Odentepyris* sp. (Hymenoptera: Bethylidae), *Aleiodes* sp., *Bracon brevicornis* (Wesmael), *Coccygidium luteum* (Brullé), *Coccygidium melleum* (Roman), *Coccygidium* sp., *Coccygidium transcaspicum* (Kokujev), *Glyptapanteles creatonoti* (Viereck), *Meteorus pulchricornis* (Wesmael), *Microplitis demolitor* Wilkinson, *Snellenius manilae* (Ashmead), *Euplectrus* sp.nr. *xanthocephalus* Girault (Hymenoptera: Bethylidae), *Campoletis chlorideae* Uchida, *Charops bicolor* (Szepligeti), *Eriborus* sp., *Ichneumon promissorius* (Erichson), *Metopius rufus* Ashmead, *Netelia* sp., *Temelucha* sp. (Hymenoptera: Ichneumonidae), *Exorista sorbillans* (Wiedemann), and *Exorista xanthaspis* (Wiedemann) (Diptera: Tachinidae) and predators: *Polistes* cf. *olivaceus* (De

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Geer), *Ropalidia brevita* Das and Gupta (Hymenoptera: Vespidae), *Cicindela* sp. (Coleoptera: Cicindelidae), *Brumoides sututralis* (F.), *C. sexmaculata*, *Coccinella transversalis* (F.), *Cycloneda sanguinea* (L.), *Harmonia octomaculata* (Fabricius), (Coleoptera: Coccinellidae), *Paederus fuscipes* Curtis (Coleoptera: Staphylinidae), *Forficula* sp. (Dermaptera: Forficulidae), *Orius* sp. (Hemiptera: Anthocoridae), *Andrallus spinidens* (F.), *Eucanthecona furcellata* (Wolff), *Podisus maculiventris* (Say) (Hemiptera: Pentatomidae), *Cosmolestes* sp., *Rhynocoris fuscipes* (F.), *Rhynocoris marginatus* (F.), (Hemiptera: Reduviidae), *Oxyopes birmamicus* Thorell (Araneae: Oxyopidae), *Lycosa* sp. (Araneae.: Lycosidae), *Marpissa* sp., *Rhene flavicomans* Simon (Araneae: Salticidae) (Muniappan et al., 2024) [99].

Nesting whitefly, *Paraleyrodes minei* Iacacrino (Hemiptera: Aleyrodidae) a native of the neotropical region was reported from India in 2018 (Mohan et al., 2019) [100]. No parasitoids were reported on this whitefly in India. A generalist neuropteran predator *A. astur* has been recorded.

Palm infesting whitefly, *Aleurotrachelus atratus* Hempel (Hemiptera: Aleyrodidae) is a native of Brazil reported from India in 2019 (Selvaraj et al., 2019) [101]. It colonizes more than 110 plant species with preference to plants belonging to the family Arecaceae. The parasitoid *E. cubensis*, a native of the neotropics fortuitously introduced to India was reported to parasitize this whitefly (Selvaraj et al., 2023) [102]. Predators, *A. astur* (Neuroptera: Chrysopidae), *Cybochephalus* spp. (Coleoptera: Cybocephalidae), *C. nigrita* and *J. pallidula* (Coleoptera: Coccinellidae) have been reported (Selvaraj et al., 2019) [101].

Woolly whitefly, *Aleurothrixus floccosus* (Maskell) (Hemiptera: Aleyrodidae) a native of neotropics reported from India in 2019 (Sundararaj et al., 2020) [103]. Parasitoid, *E. cubensis* was reported on this whitefly (Yadav et al., 2025) [87]. It is a polyphagous species, globally known to feed on 20 different plant families with a preference for citrus and guava. Predators, *A. astur* (Neuroptera: Chrysopidae), *Acletoxenus indicus* Malloch (Diptera: Drosophilidae), *C. montrouzieri* and *Scymnus nr. utilis* Hoang (Coleoptera: Coccinellidae) have been reported (Selvaraj and Sumalatha, 2021) [104].

Cassava mealybug, *Phenacoccus manihoti* Matile-Ferrero (Hemiptera: Pseudococcidae), a native of Brazil was introduced to India in 2020 (Joshi et al., 2020) [105]. The parasitoid *Anagyrus lopezi* De Santis (Hymiptera: Encyrtidae) of South American origin was imported from Benin in 2021 and field released in 2022 (Sampathkumar et al., 2021; 2022) [106,107]. Local natural enemies encountered were *Hyperaspis maindroni* Sicard, *C. sexmaculata*, *Scymnus coccivora* Ramakrishna Ayyar, (Coleoptera: Coccinellidae), *Spalgis epius* (Westwood) (Lepidoptera: Lycaenidae), *Stathmopoda* sp. (Lepidoptera: Stathmopodidae), *Nola* sp. (Lepidoptera: Nolidae), *Anatrachyntis* sp. (Lepidoptera: Cosmopterigidae), *Mallada desjardinsi* (Navas), *Aspertochrysa* (=*Pseudomallada*) *astur* (Banks), (Neuroptera: Chrysopidae), *Carpophilus mutilates* Erichson (Coleoptera: Nitidulidae), *Cardiastethus* sp. (Hemiptera: Anthocoridae) and *Indoxysticus* sp. (Araneae: Thomisidae) (Gupta et al., 2021) [108].

Mango soft scale, *Fistulococcus pokfulamensis* Hodgson & Martin (Hemiptera: Coccidae) is a native of China recorded from Karnataka, India in 2022 (Joshi et al., 2022) [109]. This pest infests mango and ten other economically important horticultural and ornamental species of plants (Sampathkumar et al., 2024) [110]. *Chilocorus nigrita*, *C. montrouzieri*, (Coleoptera: Coccinellidae) and *Dipha aphidivora* Meyrick (Lepidoptera: Pyralidae) were found to predate on this scale (Joshi et al., 2023) [111].

Apple leaf blotch miner, *Leucoptera malifoliella* (O. Costa), (Lepidoptera: Lyonetiidae), is native to Europe and has been recorded in Jammu and Kashmir, India. Besides apple, this pest also infests temperate fruit crops such as pear, cherry, and plum. So far, no natual enemies have been reported, except a few generalist predators of the family Neuroptera (Sampathkumar et al., 2023) [112].

Walnut leaf miner, *Caloptilia roscipennella* (Hübner) (Lepidoptera: Gracillariidae), is a leaf-mining moth native to Central and Southern Europe, was recorded from Kashmir, India, infesting walnut crops and causing leaf damage ranging from 15% to 20% (Mir et al., 2024) [113]. Several parasitoid species were reared from infested mines, notably of the genus *Chrysocharis* Förster (Hymenoptera: Eulophidae) and *Itoplectis maculator* (Hymenoptera: Ichneumonidae). These parasitoids provided effective control of the walnut leaf miner, with parasitization rates reaching up to 70%.

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Annona whitefly, *Aleurotrachelus anonae* (Corbett) (Hemiptera: Aleyrodidae) of neotropical origin, was reported from Karnataka, India in 2024 (Selvaraj et al., 2025) [114]. Parasitism by *Encarsia* sp. and *Eretmocerus* sp. (Hymenoptera: Aphelinidae) and predation by *Scymnus latemaculatus* Motschulsky (Coleoptera: Coccinellidae) were reported (Selvaraj et al., 2025) [114].

Carambola fruit fly, *Bactrocera carambolae* Drew & Hancock (Diptera: Tephritidae) is a native of Malaysia, southern Thailand and western Indonesia. It was reported from the Andaman Islands in 1994 (Ranganath et al., 1994) [115] and Bangladesh (Leblanc et al., 2019) [116]. However, it has not yet been reported from mainland India.

Cactus mealybug, *Hypogeococcus pungens* Granara de willink (Hemiptera: Pseudococcidae) is a native of South America reported from southern states of India in 2024. Natural enemies recorded in India are *Scymnus syoitii* Sasaji, *Brumoides suturalis* (F.) (Coleoptera: Coccinellidae) and an unidentified midge (Diptera: Cecidomyiidae) (Joshi et al., 2024a) [117].

Pit scale, *Hyaloococcus striatus* Russell (Hemiptera: Asterolecaniidae) was reported for the first time as a new invasive pest attacking sweet orange (*Citrus sinensis*) in South India (Joshi et al., 2024b) [118]. This alien scale insect poses a major threat to citrus plantations in India due to its rapid spread and severe impact. No natural enemies were observed attending the scale, making biological control options currently limited.

2.2. Invasive Weeds

Common prickly pear, *Opuntia monocantha* (Wildenow) (Cactaceae) Haworth a native of southern Brazil and Uruguay, was introduced to India in the 1780s and it became invasive from Punjab to Assam. Introduction of the cochineal insect *Dactylopius ceylonicus* (Green) (Hemiptera: Dactylopiidae) in 1795 from Brazil resulted in successful control of the weed. It became the first documented record of biological control of an alien invasive plant anywhere in the world (Zimmermann et al., 2009) [7].

Erect prickly pear, *Opuntia stricta* (Haworth) (Cactaceae) originated from Florida and West Indies region was introduced to India in the mid-1800s. Intentional introduction of *Dactylopius opuntiae* (Cockerell) (Hemiptera: Dactylopiidae) from Sri Lanka in 1926 resulted in its successful control in Southern India (Kunhikannan, 1928) [11].

Red-flower prickly pear, *Opuntia elatior* Miller (Cactaceae) is a native of tropical South America and it was introduced around 1872 (specimen deposited in the Kew Gardens). In 1926, *D. opuntiae* was intentionally introduced from Sri Lanka to control, but this also resulted in successful control of *O. stricta* (Kunhikannan, 1928) [11].

Lantana, *Lantana camara* L. (Verbenaceae) is a pantropical weed native to the tropical Americas. It was introduced to India in 1809. Ramachandra Rao (1920) [9] surveyed India and Burma and reported occurrence of 148 local insects on lantana, of which *Lantanophaga pusillidactylus* (Walker) (Lepidoptera: Pterophoridae) and *Aspondylia lantanae* Felt (Diptera: Cecidomyiidae) are fortuitously introduced insects. Muniappan and Viraktamath (1986) [119] reported fortuitous establishment of *Epinotia lantana* (Busck) (Lepidoptera: Tortricidae), a native of Mexico in southern India. Exotic natural enemies introduced were *Ophiomyia lantanae* (Froggatt) (Diptera: Agromyzidae) from Hawaii (origin Mexico) in 1921, *Teleonemia scrupulosa* Stål (Hemiptera: Tingidae) from Australia in 1941, *Uroplata girardi* Pic. (Coleoptera: Chrysomelidae) in 1969, *Octotoma scabripennis* Guerin (Coleoptera: Chrysomelidae) from Australia in 1971 (Muniappan and Viraktamath, 1986) [119].

Crofton weed, *Ageratina adenophora* (Sprengel) King and Robinson (Asteraceae) is a native of Central America, and it was introduced to India in the early twentieth century. A gall fly *Procecidochares utilis* Stone (Diptera: Tephritidae) from Mexico was introduced to India in 1963 (Rao et al., 1971) [16]. It has established in hill stations in Tamil Nadu and West Bengal and spread from India to Nepal (Sharma and Chhetri, 1977) [120] and even crossed the Himalaya and reached China in 1984 (Wan and Wang, 1991) [121]. Heavy parasitism by indigenous natural enemies has reduced its efficacy (Swaminathan and Raman, 1981) [122].

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Siam weed, *Chromolaena odorata* (L.) King and Robinson (Asteraceae) is a native of the neotropics introduced to India in the early 1840s through the botanical garden in Kolkata. A coffee planter Mr. Kalappa in Coorg upon finding *C. odorata* in his estate convinced Government of Karnataka to support a biological control project to manage it. At the request of Government of Karnataka, CIBC initiated a project resulting in the introduction of *Parachaetes pseudoinsulata* Rego Barros (Lepidoptera: Erebidae) into Karnataka, India in 1970 from Trinidad (Giriraj and Bhat, 1970) [123]. Additionally, a shipment *P. pseudoinsulata* was received from Sri Lanka in 1984, cultured and field released (Chacko and Narasimham, 1988) [124]. Sporadic occurrence of *P. pseudoinsulata* and defoliation of *C. odorata* have been reported from Kerala, Karnataka and Tamil Nadu (Arjun et al., 2016; Balaji et al., 2019) [125,126]. The eriophyid mite, *Acalitus adoratus* Keifer (Acari: Eriophyidae) was fortuitously introduced to India in 2000 (Muniappan and Bamba, 2000) [127]. The gall fly *Cecidochares connexa* (Macquart) (Diptera: Tephritidae) was introduced into Karnataka in 2002 from Indonesia (Bhumannavar et al., 2007) [128]. Later it was introduced to Kerala and Chhattisgarh (Sushilkumar, 2015) [129]. *Orimyrus orientalis* Walker (Hymenoptera: Ormyridae) has been found to parasitize *C. connexa* at moderate to high levels (NBAIR, 2013) [130].

Parthenium, *Parthenium hysterophorus* L. (Asteraceae) is a native of Mexico, introduced to India in 1950s. The natural enemy *Calligrapha* (=*Zygogramma*) *bicolorata* (Coleoptera: Chrysomelidae) was introduced to Bengaluru in 1984 (Jayanth, 1987) [131]. It has spread all over India and also moved to neighboring countries Bangladesh, Bhutan, Nepal, Pakistan and Sri Lanka. Fortuitously introduced Winter rust *Puccinia abrupta* var. *partheniicola* (Pucciniaceae) has been reported to occur sporadically in southern India from 1980s (SreeramaKumar, 2024) [132].

Water hyacinth, *Pontederia* (=*Eichhornia*) *crassipes* (Pontederiaceae) is a native of Brazil and it was introduced to Calcutta Botanical Gardens in 1890 as an ornamental plant. Currently, it has spread to all water bodies and rivers in India (Shah, 2018) [133]. Three natural enemies *Neochetina bruchi* Hustache, *Neochetina eichhorniae* Warner (Coleoptera: Curculionidae) and *Orthogalumna terebrantis* Wallwork (Acarina: Galumnidae) of South American origin were introduced to India from USA (Jayanth and Visalakshy, 1989) [134]. The mite and weevils were released in 1982 and 1983, respectively.

Water fern, *Salvinia molesta* D.S. Mitchell (Salvinaceae) is an aquatic weed and it is a native of south-eastern Brazil (Waterhouse and Norris, 1987) [135]. It was first observed in the 1955 in Vali Lake, Trivandrum, Kerala in India (Joy, 1978; Singh, 2004) [3,136]. A grasshopper, *Paulinia acuminata* De Geer (Orthoptera: Acrididae) was introduced from Trinidad in 1974 but it was not effective (Joy et al., 1981; Waterhouse and Norris, 1987) [135,137]. The weevil *Cyrtobagous salviniae* Calder and Sands (Coleoptera: Curculionidae) of Brazilian origin was imported from Australia to Bengaluru in 1982 and field released in Kerala, Jammu and Kashmir, Bhubaneshwar and Hyderabad in 1983 (Ballal, 2022) [15]. Further releases of *C. salviniae* were made in Padua village of Katni district in December, 2019 (ICAR, 2022) [138] and Satpura water reservoir at Sarni in October, 2022 (ICAR, 2024) [139] in Madhya Pradesh; Chandpur and Gadchiroli districts in Maharashtra in January 2022 (Pinjarkar, 2023) [140]; and Tulpuri lake in Durg district, Chhattisgarh (ICAR, 2024) [138].

Water lettuce, *Pistia stratioides* L. (Araceae). The origin of this plant is unclear; it has been speculated to be from Africa, Asia or South America. It is a monocotyledonous aquatic weed and occurs in water bodies and rivers all over India. A local insect, *Spodoptera* (*Namangana*) *pectinicornis* (Hampson) (Lepidoptera: Noctuidae), a native of South Asia has been reported to cause extensive damage to this weed in Kerala, India (Sankaran, 1974) [25].

Mile-a-minute vine, *Mikania micrantha* Kunth (Asteraceae) is a native of Caribbean islands introduced through Kew Botanical Garden to the Botanical Garden in Kolkata in the early 1900s (Jayaraj, 2025) [141]. A rust fungus *Puccinia spegazzinii* (Uredinales: Pucciniaceae) was released in Assam and Kerala in 2005-7 but failed to establish even though it established in Taiwan, Papua New Guinea and Fiji (Ellison and Day, 2010; Sankaran et al., 2013) [142,143].

Giant sensitive plant, *Mimosa diplotricha* C. Wright ex Saivalle (Mimosaceae) is a native of Central America to Brazil and it has been reported from Kerala, Tamil Nadu, Karnataka, Assam,

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Odisha, Uttar Pradesh, Nagaland and Tripura in India (Muniappan and Viraktamath, 1993; Priyadarshini and Sahu, 2025) [144,145]. No classical biological control action has been taken on this weed in India. It has been successfully controlled with the introduction of a host specific natural enemy *Heteropsylla spinulosa* Muddiman, Hodkinson and Hollis (Hemiptera: Psyllidae) in some Pacific Island countries and Australia (Kuniata, 2009) [146].

3. Biological Control: Successes, Constraints, Benefits, Gaps and Possible Considerations

3.1. Classical Biological Control

Successful control of the invasive weeds includes control of *O. monocantha* in northern India by the serendipitous introduction of *D. ceylonicus* in 1795 led to the idea of using insects for control of weeds (Zimmermann et al., 2009) [7]. Subsequently, control of the cactuses, *O. stricta and O. elatior* in southern India was achieved by the intentional introduction of *D. opuntiae* from Sri Lanka in 1926 (Kunhikannan, 1928) [11]. The invasive water fern, *S. molesta* was successfully controlled in the states of Kerala, Chhattisgarh, Madhya Pradesh and Maharashtra by the introduction of the weevil *C. salviniae* from Australia in 1982 (Joy, 1978) [136]. Substantial control of the weed parthenium *P. hysterophorus* has been achieved by introducing *C. bicolorata* (Sushilkurmar, 2009) [147].

Invasive pests of temperate fruit crops, woolly apple aphid *E. lanigerum,* and San Jose scale *C. perniciosa* are under control by the introduced natural enemies, however, there is a need for inoculative release of their natural enemies early in the spring to catch up with the host population that emerges from diapause (Singh, 2020; Gupta, 2005) [21,26]. Invasive pests of tropical crops, coffee green scale *C. viridis*, cottony cushion scale *I. purchasi*, citrus mealybug *P. citri,* papaya mealybug *P. marginatus*, Leucaena psyllid *H. cubana,* and eucalyptus gall wasp *L. invasa* are under control by the intentionally introduced natural enemies requiring minimal or no additional efforts (Singh, 2004; Jalali and Singh, 1989; Yousuf et al., 2017; Poorani et al., 2024) [3,50,62,75]. Satisfactory control of cotton mealybug *P. solenopsis* has been achieved by the fortuitously introduced parasitoid *A. arizonensis* (Ram and Saini, 2010) [72]. Additionally, fortuitously introduced parasitoids *E. cubensis*, *E. dispersa, E. guadeloupe*, and *E. haitiensis* have been providing control of invasive whiteflies *A. dispersus, A. rugioperculatus, A. trachoides, A. floccosus*, and *A. atratus* (Viraktamath, 2002; Selvaraj et al., 2016; Poorani and Thanigairaj, 2017; Yadav et al., 2025) [53,87,93,148]. There has always been varying degrees of association between local natural enemies and introduced natural enemies in managing invasive insect pests.

Within India, parasitoids, *E. flavoscutellum and O. pallidipes intentionally* transferred from the northeastern region to southern region for control of sugarcane woolly aphid, *C. lanigera* and banana skipper, *E. torus*, respectively, have given satisfactory control of both pests (Srikanth et al., 2015; Poorani et al., 2020) [68,81].

Some introduced natural enemies have extended their host range beyond their intended target(s) and controlled additional introduced exotic pests. The coccinellid beetle *C. montrouzieri* introduced from Australia in 1898 for control of coffee green scale *C. viridis* is also providing control of several introduced and native mealybugs and scale insects, *Nipaecoccus viridis* (Newstead), *Maconellicoccus hirsutus* (Green), *Planococcus lilacinus* (Cockerell), *Ferrisia virgate* Cockerell, *Rastrococcus iceryoides* (Green) , *Rastrococcus invadens* Williams, *Coccidohystrix insolita* (Green), *Planococcus minor* (Maskell), *Pseudococcus longispinus* (Targioni Tozzetti) (Hemiptera: Pseudococcidae), *Insignorthezia insignis* Browne (Hemiptera: Ortheziidae); *Pulvinaria psidii* (Maskell), *Drepanococcus chiton* (Green), *Pulvinaria polygonata* Cockerell, *Saissetia coffeae* Walker, *Fistulococcus pokfulamensis* Hodgson and Martin (Hemiptera: Coccidae) and *Uhleria* (*Eriococcus*) *araucariae* (Maskell) (Hemiptera: Eriococcidae) (Singh, 2004; Sampathkumar et al., 2024) [3,110]. An exotic parasitoid *T. remus*, introduced to India from Papua New Guinea for control of *S. litura* and *A. Janata* in 1963 (Rao et al., 1971) [16], has proven to be one of the effective agents for controlling fall armyworm *S. frugiperda* that invaded India in 2018 (Muniappan et al., 2024) [99]. Exotic parasitoids introduced, *T. evanescens* for stem borers, and *T.*

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brasiliensis and *T. pretiosum* for *Helicoverpa* sp. (Lepidoptera: Noctuidae) have been reported to parasitize diamondback moth *P. xylostella* in India (Singh, 1994; Jalali, 2013) [31,34].

Biotic constraints such as local hyper parasitoids attacking introduced parasitoids; and parasitoids attacking predators of invasive insect pests and introduced natural enemies of invasive weeds have reduced efficacy of the intended natural enemies. The parasitoid, *A. arizonensis* of cotton mealybug *P. solenopsis* is attacked by hyper parasitoids *Promuscidea unfasciativentris* Girault, *Myiocnema comperei* Ashmead, *Prochiloneurus albifuniculus* (Hayat, Alam and Agarwal), *Prochiloneurus pulchellus* Silvestri, *Prochiloneurus aegyptiacus* (Mercet) (Hymenoptera: Encyrtidae) and *Marietta leopardina* Motschulsky (Hymenoptera: Aphelinidae) (Ram and Saini, 2010) [72]. *Lantana camara* natural enemies, *O. lantanae* is attacked by eight species of chalcidoid parasitoids (Beeson and Chatterjee, 1940) [149] and *T. scrupulosa* by an egg parasitoid, *Erythmelus teleonemiae* (Subba Rao) (Hymenoptera: Mymaridae) (Jayanth and Visalakshy, 1992) [150]. Four parasitoids, *Diameromicrus kiesenwetteri* (Meyr) (Hymenoptera: Torymidae), *Syntomopus* sp. (Hymenoptera: Pteromalidae), *Bracon* sp. (Hymenoptera: Braconidae), and *Eurytoma* sp. (Hymenoptera: Eurytomidae) identified on *P. utilis* impacted its efficacy on control of Crofton weed *A. adenophora* (Swaminathan and Raman, 1981) [122]. The parasitoid, *Ormyrus orientalis* has been observed to attack *C. connexa* the natural enemy of Siam weed *C. odorata* in Bengaluru (NBAIR, 2013a) [130]. Parasitoids *Aprostocetus* sp. (Hymenoptera: Eulophidae), *Homalotylus turkmenicus* Myartseva, *H. flaminus* Dalman (Hymenoptera: Encyrtidae), and *Metastenus concinnus* Walker (Hymenoptera: Pteromalidae) attack immature stages of the ladybeetle *Hyperaspis maindroni* Sicard (Coleoptera: Coccinellidae). *Tetrastichus* sp. (Hymenoptera: Eulophidae) and *Brachycyrtus* sp. (Hymenoptera: Ichneumonidae) parasitize larvae of *Mallada desjardinsi* (Navas) (Neuroptera: Chrysopidae) (Mani and Shylesha, 2021) [77]. The parasitoid *Palexorista* sp. (Diptera: Tachinidae) and predators, *Andrallus spinidens* (F), *Eocanthecona furcellata* Wolff (Hemiptera: Pentatomidae) and *Sycanus pyrrhomelas* Walker (Hemiptera: Reduviidae) were reducing the population of the leaf feeding beetle *C. bicolorata* introduced for control of parthenium (NBAIR, 2013b) [151].

There are gaps in implementing classical biological control of introduced insect pests and weeds. For example, *I. insignis* and *Q. erythrinae* were effectively controlled by introduced natural enemies in other countries (Booth et al., 1995; Fowler, 2004; Kaufman et al., 2020) [35,36,70] and India could consider introducing them. Similarly, effective natural enemies that were used to control invasive weeds *M. diplotricha* and *P. stratioides* in other countries could be considered for introduction [Kuniata, 2009; Waterhouse, 1994) [146,152]. Efforts made to manage *M. micrantha* by introducing the rust fungus should be followed up (Sankaran et al., 2013) [143]. Some agents introduced for control of invasive weeds are yet to be distributed widely in India. For example, *Octotoma scabripennis* was established in northern India in 1971 and it is yet to be introduced to southern India and *C. connexa* established in Bengaluru area in 2002 has not been released in northeastern India where *C. odorata* is a serious problem.

Little or no work has been done on assessing economic impact of controlling invasive insect pests and weeds by introduced exotic natural enemies in India. In one incidence, it was estimated that India benefited from US$540 million to US$1.34 billion by introducing the parasitoid *A. papayae* for control of papaya mealybug *P. marginatus* (Myrick et al., 2014) [153]. In another case, adoption of biological control strategies for management of rugose spiraling whitefly on coconut and oil palm plantations saved Indian Rs 9,500/ha (Selvaraj et al., 2024) [154].

3.2. Augmentative Biological Control

Augmentative control has two strategies, inoculative and inundative release of natural enemies. Agents for augmentative biological control are selected based on their efficacy, biology, ease of rearing, cropping situation, seasonality, and cultural practices. Trichogrammatids are the most commonly used agents in inundative augmentative biological control. According to Jalali (2013) [34], there are 19 introduced exotic species and 32 locally identified species of *Trichogramma* in India of which, *T. chilonis*, *T. japonicum*, *T. achaeae*, *T. embryophagum*, *T. pretiosum*, *T. brasiliensis*, and *T. bactrae*

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are commonly used in augmentative control, mostly for the lepidopteran pests. To cite a few examples, Krishnamoorthy et al. (2013) [155] recommended release of either one of the local parasitoids *T. bactrae*, *T. chilonis* or the exotic parasitoid *T. brassicae* at the rate of 50,000 adults per week per hectare for the effective control of *P. xylostella*. Singh (1994) [31] recommended release of *T. embryophagum* at 2,000 adults/tree at weekly intervals, starting when the first moth is caught in the pheromone trap for codling moth *L. pomonella* management. Additionally, Singh (1994) [31] has given a list for augmentative releases of *T. brasiliensis, T. chilonis, T. pretiosum, A. mali, L. dactylopii, N. cardinalis, C. montrouzieri*, and *Phytoseiulus persimilis* and their dosages for control of various vegetable and fruit crop insect and mite pests in India. Inoculative augmentation is also used for initial establishment of introduced natural enemies to suppress pest populations that emerge in early spring in temperate crops, and to manage outbreaks of native and introduced insect pests.

3.3. Conservation Biological Control

Conservation biological control is practiced by preserving native, naturalized, and introduced natural enemies by selective use of insecticides, environmental modification by enhancing vegetational diversity, mixed cropping, trap cropping, planting flower crops, and adopting safe management technologies. Conservation biological control plays a major role in successes of classical and augmentative biological control by enhancing the efficacy of natural enemies. According to Gurr et al. (2000) [156] indiscriminate pesticide use is a major negative factor in conservation biological control; however, pesticide use in India is low at 0.4 kg/ha compared to 1.83 Kg/ha in China. Additionally, pesticide use has been declining from 0.44 kg/ha in 1990 to 0.37 kg/ha by 2021 (Reddy et al., 2024) [157], due to implementation of integrated pest management (IPM). There are 36 Central Integrated Pest Management Centers (CIPMC) located in 28 states and two union territories are promoting use of biopesticides and natural enemies emphasizing conservation biological control. It is a positive and encouraging development which strengthens conservation biological control and enhances environmental safety in India.

There are several instances of successful conservation biological control due to creation of safer environment for natual enemies. *Cryptolaemus montrouzierie* introduced for management of *C. viridis* has provided control of several mealybugs and scale insects (Singh, 2004) [3]. Native and naturalized natural enemies have successfully managed South American tomato leaf miner, *P. absoluta*, American serpentine leafminer *L. trifolii*, Jack Beardsley mealybug *P. jackbeardsleyi*, Madeira mealybug *P. madeirensis*, fall armyworm *S. frugiperda*, and some of the recently introduced whiteflies.

3.4. General Observations

Eventhough varing degrees of success in managing invasive insect pests and weeds has been achieved by adopting biological control, it would be worthwhile to address some of the exotic pests of economical and environmental importance, such as, mango fruit borer *C. eutraphera*, red banded mango caterpillar, *D. sublimbalis*, coconut eriophyid mite *A. gurerreronis*, Erythrina gall wasp *Q. erythrinae*, tobacco thrips *T. parvispinus,* mango soft scale *F. pokfulamensis*, carambola fruit fly *B. carambolae* and others. When no effective natural enemies are found, effective alternate IPM components should be explored.

An invasive insect pest of coconut trees, the hispine beetle *Brontispa longissima* (Gestro) (Coleoptera: Chrysomelidae), a native of Southeast Asia has established in the neighboring countries Maldives and Myanmar (Shafia, 2004; Rethinam and Singh, 2007) [158,159] and India should take necessary measures to prevent its introduction and be ready to take appropriate control measures, when it invades. One of the option available is introduction of the parasitoids *Asecodes hispinarum* Boucěk and *Tetrastichus brontispae* (Ferrière) (Hymenoptera: Eulophidae), that has given successful results in several Asia-Pacific countries (Rethinam and Singh, 2007) [159]. An invasive weed, giant sensitive plant *Mimosa pigra* L. (Leguminosae) a native of neotropics has established in Myanmar and Sri Lanka (Marambe et al., 2014) [160]. The report of its occurence in India by Welgama et al. (2022) [161] is an error. For this invasive weed also, India should monitor its borders closely to take up

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appropriate measures to prevent its introduction as well as to contain and eradicate it, if and when it gets introduced.

4. Conclusions

First documented biological control of a weed took place in India in 1795 leading to initiation of biological control programs in the world. However, until the start of the Project Directorate of Biological control in 1977 (presently, ICAR-National Bureau of Agricultural Insect Resources), most of the activities were sporadic and lacked systematic implementation and follow up. Successful control has been achieved of the weeds, *O. monacantha, O. stricta, O. elatior,* and *S. molesta,* and insect pests, *A. dispersus, C. viridis, A. rugioperculatus, C. perniciosa, H. cubana, I. purchasi, L. invasa, P. marginatus, P. manihoti,* and *P. solenopsis,* by adopting classical biological control. The coccinellid beetle, *C. montrouzieri* introduced from Australia in 1898 has contributed to control of several species of mealybugs and scale insects. Partial control has been achieved of *L. camara, C. odorata, E. lanigerum, A. atratus, A. floccosus,* and *P. hysterophorus*. Augmentative control has been adopted using both exotic and local natural enemies for *E. lanigerum, P. opercullela, p. xylostella, L. pomonella, P. absoluta,* and *S. frugiperda*. Efficacy of some of the introduced natural enemies of weeds has been reduced by the local parasitoids, predators of insect pests by parasitoids, and parasitoids by hyperparasitoids. In general, India has benefited in billions of dollars by managing invasive species and safeguarding the environment by adopting biological control programs. The declining trend in use of chemical pesticides in recent years is a step in the right direction for sustainable development.

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