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Review Article

Role of *Trichogramma* in biological control of pests in India: A concise review

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ABSTRACT: An eco-friendly and sustainable alternative to chemical pesticides, biological control includes *Trichogramma*, a genus of minute insect egg parasitoids, which is widely distributed and adaptable to various agro-climatic conditions in India. It plays an important role in the biological control of insect pests infesting horticultural, floricultural, agricultural, and forestry crops. In India, various species of this genus are widely utilised to control important lepidopteran pests that damage crops, including vegetables, rice, cotton, sugarcane, and maize. The integration of these biological control agents in pest management programs not only reduces dependency on chemical inputs but also enhances crop yield and quality, promoting environmental and human health. The review highlights the key challenges, including field efficacy, advancements, compatibility with other control methods, biology, mass multiplication and adoption barriers among farmers and potential strategies to enhance *Trichogramma's* role in Indian agriculture.

KEYWORDS: Biological control, egg parasitoid, host range, Hymenoptera, IPM

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INTRODUCTION

Throughout the world, people widely use *Trichogramma* spp. as egg parasitoids for the biological control of insect pests. An era of indiscriminate use of synthetic pesticides or chemicals led to chemical pollution in the environment, posing health risks to humans. IPM relies heavily on biological control, releasing the *Trichogramma* species into the field, which gained popularity as a biocontrol agent due to their large-scale commercial production. Researchers have recorded Trichogrammatids controlling various lepidopterous insect pests. Smith (1996) observed *Trichogramma* as the most useful parasitoid for over 100 years. 40 countries around the world apply *Trichogramma* spp. as an important biological control agent (Zhang *et al.*, 2021). India widely uses *Trichogramma* to control various insect pests that attack rice, maize, sugarcane, cotton, vegetables, and fruits. More than 1000 species worldwide represent egg parasitoids of the family Trichogrammatidae. In India, the Trichogrammatidae family encompasses more than 200 species under 31 genera, out of which 44 species (Table 1) of *Trichogramma* (Noyes, 2024). The three-segmented tarsal segments easily distinguish members of this family, which range in size from 0.2 to 0.5 mm. They mainly parasitize various pests belonging to the orders Lepidoptera, Hemiptera, and some Coleoptera, Diptera, and Thysanoptera. People generally accept trichogrammatids as a biological control method for lepidopteran pests in agriculture and forestry (Doutt & Viggiani, 1968; Debach & Rosen, 1991). Recently, works have been carried out by many researchers (Yousuf *et al.,* 2015) on the novel genus *Trichogramma*, and it has also been used as an important biological control agent throughout the world, and they have provided the host range of *Trichogramma* spp. with their diagnosis from India.

IDENTIFICATION

Trichogramma is one of the 98 genera under the family Trichogrammatidae, whose species are egg parasitoids. Trichogrammatidae are little insects, measuring from 0.2 to 1.5 mm in size. Almost 230 species recorded globally, as egg parasitoids of the genus *Trichogramma* Westwood are widely employed to combat agricultural pests in both annual and perennial crops (Querino & Zucchi, 2019; Zhang *et al.*, 2021). Accurate identification is crucial for the efficacy of a biological control program targeting *Trichogramma* species due to its principal application. They are challenging to recognise due to their minute size and similar physical traits. The characteristics of male genitalia are crucial for the systematics of *Trichogramma,* facilitating precise identification at the species level. Recently, some researchers have also contributed to the identification and exploration

of *Trichogramma* spp.; Khan *et al.* (2020) identified a new species of *Trichogramma yousufi* from an unknown lepidopterous egg from a poplar tree. Khan *et. al.* (2018) provided data and studied morphometric characters of different *Trichogramma* spp., which were reared in different laboratories in India.

Taxonomic classification of *Trichogramma*

Order: Hymenoptera

Superfamily: Chalcidoidea

Family: Trichogrammatidae

Sub family: Trichogrammatinae

Tribe: Trichogrammatini

Genus: *Trichogramma*

BIOLOGY

Trichogramma species start their life cycle when the eggs hatch, which usually takes 3 to 4 days. In order to lay its eggs inside a host egg, the female finds the egg, drills a hole in the chorion, and then lays several eggs inside. As the bollworm egg is being parasitised, pressure from inside pushes a small drop of yolk to come out through the oviposition hole. The female eats this egg, which makes her live longer. When the female lays an egg, she releases a toxin that makes the innards of the egg start to break down. The eggs hatch in about 24 hours, and the larvae grow quickly through three stages that look like sacs. By the third larval instar (3 to 4 days after parasitism), the host egg darkens as black granules accumulate inside the chorion. The prepupal stage, where the adult features form, comes next, followed by the pupal stage. The number of eggs laid by a female ranges from 20 to 120, depending on the species, host, and the female's lifespan. Factors such as food availability (sugar and water), the presence of host eggs, temperature, humidity, and the female's activity influence the female's lifespan. Under laboratory conditions, a female can parasitise between 1 and 10 bollworm eggs daily, or 10 to 190 throughout her entire life. Larger females tend to parasitise more eggs than smaller ones. Females fed both honey and young bollworm eggs live an average of 11 days, while those given only honey survive for only 3 days. The darkening of the chorion and the presence of an exit hole are clear signs of parasitism by *Trichogramma* spp. (Samara, 2005). Recently, some researchers also studied the effect on the biology of *Trichogramma pretiosum* due to Bt toxin extracted from the pollen of Maize crops (Maria *et al.,* 2017).

Augmentation and efficacy of *Trichogramma* spp.

Biswas *et al.* (2021) looked at how *T. chilonis* releases affected the growth of *Leucinodes orbonalis* in brinjal. After 30 generations of breeding on *L. orbonalis* eggs, they found that releasing 100,000 *T. chilonis* per hectare was the best way to get rid of shoot infestations (87.17% reduction) from 15 to 90 days after transplanting. Similarly, the release significantly reduced fruit infestation (68.44%) from 50 to 140 days after transplanting compared to the control. Even though *Trichogramma* spp. has shown effectiveness against numerous lepidopteran pests, the accessibility of Tricho-cards remains a significant limitation. The unavailability of technology for long-term storage of Tricho-cards has created an obstacle for the commercial production of Tricho cards. A method developed at ICAR NBAIR concerning the long-term storage of Tricho-cards by inducing diapause has addressed this crucial challenge (Ghosh & Ballal, 2017, 2018). Pawar *et al.* (2023) studied the enhancing biocontrol potential of *Trichogramma chilonis* against borer pests of wheat and chickpeas. Ruhela *et al.* (2020) investigated the biological control of *Trichogramma chilonis* ishii and *Tetrastichus Howard* (Oliff) for control of the sugarcane upper shoot borer (*Scirpophaga nivella* Fabricius). Singh *et al.* (2020) studied the bio-efficacy of egg parasitoids *Trichogramma chilonis* (ishii) against spotted stem borer *Chilo partellus* in kharif maize (Table. 1). Manohar *et al.* (2020) studied the response of *Trichogramma achaeae* (Nagaraja and Nagarakatti), *Trichogramma pretiosum* Riley, *Trichogramma chilonis* Ishii and *Trichogramma pieridis* Nagaraja and Prashanth against *Tuta absoluta* under laboratory conditions. Sharma *et al.* (2020) investigated a flood release of Trichogrammatids against butterflies compared to conventional chemical cultivators by releasing *Trichogramma chilonis* Ishii and *Trichogramma japonicum* Ashmead to the sugarcane borer *Chilo infuscatellus*, *Scirpophaga excerptalis*. According to Variya *et al.* (2021), inundative releases of *Trichogramma bactrae* at a rate of 150,000 individuals per hectare, conducted twice during the flowering stage and three times during the boll maturation stage at weekly intervals, resulted in a rosette flower percentage of 16.96%, compared to 22.06% in the control group. Additionally, green boll damage was recorded at 18.24%, while the control group showed 22.51%. At harvest, open boll damage was noted at 7.85% and locule damage at 4.22%, compared to 11.03% and 5.32% in the control.

Success stories of *Trichogramma* spp.: case studies and impacts

Trichogramma spp. are important parasitoid wasps widely used in biological control programs around the world. Acting as an eco-friendly insecticide, they target and kill insect pests without harming other natural flora and fauna. These wasps have been utilised for decades to control various butterfly pests. In the early 20th century, entomologists began cultivating *Trichogramma* commercially for biological control purposes. In India, *Trichogramma minutum*, the

Table 1. Indian species of *Trichogramma* with their host range (Yousuf *et al.*, 2015)

S. No.	***Trichogramma* spp.**	**Host range**
1	*Trichogramma achaeae* (Nagaraja & Nagarkatti, 1969)	*Pectinophora gossypiella, Spodoptera litura* and *Tiracola plagiata Parasa consocia, Parnara guttata, Pelopidas mathias, Philosamia cynthiaricini, Pieris rapae, Plutella xylostella, Procera sacchariphagus, Procera venosatus, Prodenia litura, Prodesaia kurosawai, Psara* spp., *Samia cynthia, Scirpophaga excerptalis, Scirpophaga incertulas, Scirpophaga innotata, Scirpophaga nivella, Scirpopha gasp., Sesamia inferens, Sitotroga cerealella, Spilarctis obliqua, Spodoptera litura, Spodoptera mauritiana, Tiracola plagiata, Tricho plusiani, Tryporyza inceretulas* and unidentified *Lycaenid, Noctuid, Pyralid* and *Sphingid eggs.*
2	*Trichogramma agriae* (Nagaraja, 1973)	*Agrius convolvuli and Corcyra cephalonica*
3	*Trichogramma breviciliata* (Yousuf & Hassan, 2007)	*Eutectona machaeralis, Hyblaea puera, Hasora alexis*
4	*Trichogramma brassicae* (Bezdenko, 1968)	*Pectinophora gossypiella* and *Spodoptera litura*
5	*Trichogramma breviflagellata* (Yousuf, 2010)	*Corcyra cephalonica* (Snellen), on sugarcane
6	*Trichogramma brevifringiata* (Yousuf & Shafee, 1988)	*Chilo infuscatellus*
7	*Trichogramma cacoeciae* (Marchal, 1927)	*Chilo partellus*
8	*Trichogramma chilonis* (Ishii, 1941)	*Agrius cingulata, Agrius convolvuli, Ampilliadio scoridea, Anomis flava, Arctia coerulea, Samia cynthia, Scirpophaga excerptalis, Scirpophaga incertulas, Scirpophaga innotata, Scirpophaga nivella, Scirpophaga* sp., *Sesamia inferens, Sitotroga cerealella, Spilarctis obliqua, Spodoptera litura, Spodoptera mauritiana, Tiracola plagiata, Trichoplusia ni, Tryporyza inceretulas* and unidentified *Lycaenid, Noctuid, Pyralid* and *Sphingid* eggs.
9	*Trichogramma chilotraeae* (Nagaraja & Nagarkatti, 1969)	*Chilo partellus, Chilo supressalis, Corcya cephalonica Agrius convolvuli, Bactra* sp., *Chilo infuscatellus, C. partellus, C. suppressalis, Corcyra cephalonica, Helicoverpa armigera, Pelopidas mathias, Ostrinia furnacalis* and *Trichoplusia ni.*
10	*Trichogramma convolvuli* (Nagaraja, 1996)	*Agrius convolvuli* and *Corcyra cephalonica*
11	*Trichogramma cuttackensis* (Nagaraja, 1996)	*Psalis* spp.
12	*Trichogramma cordubensis* (Vargas & Cabello,1985)	*Corcyra cephalonica*
13	*Trichogramma danaidiphaga* (Nagaraja & Prashanth, 2010 in Nagaraja & Mohanraj, 2010)	*Danaus chrysippus* and *Corcya cephalonica*
14	*Trichogramma danausicida* (Nagaraja, 1996)	*Danaus chrysippus* and *Corcya cephalonica*
15	*Trichogramma flandersi* (Nagaraja & Nagarkatti, 1996)	*Agrius convolvuli, Chilo infuscatellus* and *Corcyra cephalonica*
16	*Trichogramma hebbalensis* (Nagaraja, 1996)	*Corcyra cephalonica*
17	*Trichogramma hesperidis* (Nagaraja, 1973)	Hesperiid eggs on paddy leaves
18	*Trichogramma japonicum* (Ashmead, 1904)	*Aglossa dimidiata, Chilo auricilius, Pelopidas Sitotroga cerealella, Susumia exigua, Tetramoera schistaceana, Trichoplusia ni, Tryporyza incertulas, Tryporyza innotata* and *Tryporyza novella, Trichoplusia ni*
19	*Trichogramma kankerensis* (Yousuf & Hassan, 2008)	*Corcyra cephalonica*
20	*Trichogramma kashmirica* (Nagaraja *et al.*, 2007)	*Sciomyzid* eggs
21	*Trichogramma latipennis* (Yousuf & Hassan, 2008)	*Corcyra cephalonica*
22	*Trichogramma manii* (Nagaraja & Gupta, 2007)	*Deudorix isocrates*

Table 1. Continued...

23	*Trichogramma rabindrai* (Nagaraja & Mohanraj, 2010)	*Scirpophaga incertulas* and *Tryporyza incertulas*
24	*Trichogramma pallidiventris* (Nagaraja, 1973)	*Corcyra cephalonica, Scirpophaga incertulas* and *Tryporyza incertulas*
25	*Trichogramma plasseyensis* (Nagaraja, 1973)	*Chilo auricillius, Corcyra cephalonica, Hyblaea puera, Chilo auricilius, Chilo infuscatellus, Chilo terrenellus, Chilo tumidicostalis, Corcyra cephalonica, Eutectona machaeralis, Helicoverpa armigera, Hyblaea puera* and *Ostrinia furnacalis*
26	*Trichogramma poliae* (Nagaraja, 1973)	*Chilo auricilius, Chilo infuscatellu, Chilo tumidicostalis, C. fulgurita*
27	*Trichogramma raoi* (Nagaraja, 1973)	*Achaea Janata, Corcyra cephalonica, Eutectona machaeralis, Achaea janata, Boarmia variegate, Corcyra cephalonica, Eurema sp. Eutectona machaeralis, Hyblaea puera, Laspeyresia koenigana and Naranga aenescens*
28	*Trichogramma sankarani* (Nagaraja, 1996)	*Agrius convolvuli*
29	*Trichogramma semblidis* (Aurivillius, 1898)	*Calopodes ethlius, Chilo infuscatellus, Acantholyda pinnivora, Achaea Janata, Cactoblastis cactorum*
30	*Trichogramma australicum* (Girault, 1912a)	*Cactobalstis pomonella, Chilo indicus*
31	*Trichogramma embryophagum* (Hartig, 1838)	*Acatholuda nemeroles, Acantholyda pinivora, Anthraea pernyi, Archips rosanus, Barathra brassicae, Bupalus piniarius, Cacoecia rosana, Carpocapsa pomonella, Cydia pomonella, Dasychira pudibunda, Dendrolimus pini, Dendrolimus spectabilis, Euproctis chrysorrhoea, Orthosia circellaris. Spilonota ocellana, Thaumetopoea pityocampa, Thaumetopoea wilkinsoni, Thera fermata, Thera obeliscata, Tmetocera ocellana, Tortrix viridana, Traumatocampa pityocampa, Zeiraphera diniana* and *Zeiraphera griseana*
32	*Trichogramma exigum* (Pinto & Platner, 1978)	*Clostera cupreata, Ephestia cautella, Helicoverpa armigera, Heliothis virescens, Sitotroga cerealella*
33	*Trichogramma minutum* (Riley, 1871)	*Achaea janata, Achroia grisella, Achrobasis juglandis, Acrobasis* spp., *Adoxophes orana, Albama arqillacea, Agraulis vanullae, Alletia argillacea, Alsophila pometaria, Amelia ivana, Ametastegia glabrata, Amorbia emigratella, Anomis erosa, Anomis* spp., *Archips excessana, Bactra turuculenta, Chilo* spp., *Corcyra cephalonica*
34	*Trichogramma evanescens* (Westwood, 1833)	*Anomis flava, Chilo suppressalis, Cocyttodes coerulea, Ephestia cautella, Corcyra cephalonica, Theresimima ampelophaga, Tholera popularis, Trachea triplicis, Tribolium castaneum, Trichoplusia ni, Triphaena pronuba, Virachola livia, Xestia c-nigrum, Zeiraphera diniana* and *Zygaena* spp.
35	*Trichogramma pallidiventris* (Nagaraja, 1973)	*Helicoverpa armigera, Plutella xylostella, Corcyra cephalonica, Corcyra cephalonica, Tryporyza incertulas*
36	*Trichogramma pieridis* (Nagaraja & Mohanraj, 2010)	*Corcyra cephalonica, Clostera cupreata, Catopsilia pyranthe*
37	*Trichogramma flandersi* (Nagaraja & Nagarkatti, 1969)	*Corcyra cephalonica, Tryporyza incertulas*
38	*Trichogramma perkinsi* (Girault, 1912)	*Catopsilia pyranthe, Corcyra cephalonica, Clostera cupreata*
39	*Trichogramma pintoi* (Voegele, 1982)	*Corcyra cephalonica*
40	*Trichogramma pretiosum* (Riley, 1879)	*Helicoverpa armigera, Eggs of Chrysoperla* spp. *(Neuroptera: Chrysopidae)* (Zucchi *et al.*, 2010)*; Corcyra cephalonica* and *of Heraclides astyalusn* on *Citrus* spp. (Querino *et al.*, 2017)
41	*Trichogramma semifumatum* (Perkins, 1910)	*Agrius convolvuli, achaea Janata, Corcyra cephalonica*
42	*Trichogramma dendrolimi* (Matsumura, 1926)	*Acantholyda pinnivora, Achaea janata, Cactoblastis cactorum, Corcyra cephalonica*
43	*Trichogramma thalense* (Pinto & Oatman, 1985)	*Acantholyda pinnivora*
44	*Trichogramma californicum* (Nagaraja & Nagarkatti,1973)	*Corcyra cephalonica, Clostera cupreata*

Table 2. Assessment of the bio-efficacy of Key *Trichogramma* spp. in India

	***Trichogramma* spp.**	**Host insects**	**Host plants**	**Efficacy (%)**	**References**
1	*Trichogramma japonicum* *Trichogramma brasiliensis*	*Corcyra cephalonica* *Eutectona machaeralis* *Hyblaea puera* *Corcyra cephalonica* *Eutectona machaeralis* *Hyblaea puera*	Teak	36.20% 32.40% 29.60% 47.20% 45.60% 39.40%	(Ahmad, 1990)
	Trichogramma chilonis *Trichogramma brasiliensis* *Trichogramma japonicum* *Trichogramma pretiosum*	*Eutectona machaeralis* *Eutectona machaeralis* *Eutectona machaeralis* *Eutectona machaeralis*	Teak	52% 58% 37% 40%	(Joshi *et al.,* 2007)
3	*Trichogramma raoi* *Trichogramma plasseyensis* *Trichogramma breviciliata*	*Hyblaea puera* *Eutectona machaerali* *Hyblaea puera* *Eutectona machaeralis* *Hasora alexis*	Teak	*38.80%* 37.20% 37.70% 39.50% 36.10%	(Yousuf, 2008)
4	*Trichogramma chilonis*	*Corcyra cephalonica* *Spodoptera litura*	Reared on Grain Mixture (In Laboratory)	*61.17%* 80.31%	(Puneeth & Vijayan, 2013)
5	*Trichogramma chilonis*	*Chilo partellus*	Fodder Maize	41.9 to 42.8%	(Jalali & Singh, 2003)
6	*Trichogramma chilonis*	*Chilo partellus*	Maize	44.8% to 43.1%	(Kumar *et al.*, 2011)
7	*Trichogramma achaeae* *Trichogramma pretiosum* *Trichogramma bactrae*	*Tuta absoluta*	Tomato	50% 51.1% 68.2%	(Ballal *et al.*, 2016)
8	*Trichogramma chilonis*	*Chilo partellus*	Kharif Maize	62.4%	(Singh *et al.*, 2020)
9	*Trichogramma yousufi*	*Spodoptera exigua* *Spodoptera litura*	*Zea mays*	40.82%	(Khan *et al.*, 2020)

most common species, was first cultivated in 1926 to target *Sitotroga cerealella* eggs. Today, *Trichogramma* is effectively used to protect crops such as cotton, sugarcane, vegetables, sugar beet, orchards, and forests, contributing significantly to sustainable pest management. The use of *Trichogramma* in field trials against the sugarcane borer began in Karnataka in 1930 (Kunhikanan, 1931), and there have been several success stories. India has released *Trichogramma evanescens* to combat the sugarcane borer, spotted cotton, coffee, Teak leafhopper, and tea and lac pests (Beeson, 1941). In Tamil Nadu, the release of *Trichogramma chilonis* reduced damage caused by *sacchariphagus indicus* (Sithanantham *et al.,* 1973). Large-scale field trials in Tamil Nadu showed the usefulness of *Trichogramma* (Vardharajan, 1976; Sithanantham, 1980; Solayappan, 1980). In Andhra Pradesh, researchers found that releasing *Trichogramma chilonis* in sugarcane effectively controlled *C. infuscatellus* (Rao, 1980). Yadav *et al.* (1985) studied the release of *Trichogramma chilonis*

against *Helicoverpa armigera* from Gujarat. In north Bihar, the release of *Trichogramma* spp. gave encouraging results against *C. infuscatellus* and *C. auricilius*. Thakur *et al.* (1991) introduced *Trichogramma chilonis* against the Anar butterfly in Kullu Valley. Easwaramoorthy and David (1992) cited that *Trichogramma chilonis* was widely used in India against *Chilo infuscatellus*, *C. sacchariphagusindicus* and *C. auricilius*, while *Trichogramma japonicum* was generally employed against *Scirpophaga excerptalis*. Krishnamoorthy and Mani (1996) recorded the bio-suppression of *Helicoverpa armigera* on tomato by *Trichogramma brasiliensis* and *Trichogramma pretiosum.* Mani and Krishnamoorthy (1999) recorded the natural parasitisation of *Trichogramma chilotraeae* in pomegranate butterflies in Bengaluru. *Trichogramma chilonis* (=*T. minutum*) 9,250 parasitoids were released at Nilambur in 1937, in three areas: Aravallikavu, Mundakadavu and Pokode. Also, 225 unidentified *Trichogramma*, obtained from eggs of *Eutectona machaeralis* from Burma, were released in two areas: Aravallikavu and Mundakadavu (Beeson, 1941). Patil and Naik (1997) tested *Trichogramma spp.* against *Hyblaea puera.* Yousuf (2005) and Joshi *et al.* (2007) tested the laboratory and field efficacy of four *Trichogramma* spp.: *T. pretiosum*, *T. brasiliensis*, *T. japonicum* and *T. chilonis* against the teak skeletoniser, *Eutectona machaeralis* (Table 2). Yousuf (2008) did their laboratory bioefficacy of three endemic species, *Trichogramma raoi*, *T. plasseyensis* and *T. breviciliata* against *Hyblaea puera*, E. *machaeralis* (Table 2).

Advanced mass rearing methods for *Trichogramma* spp. (NBAIR)

The nucleus culture of *C. cephalonica* in egg form was sourced from NBAIR, Bangalore, which was mass-reared and housed in a designated room. Bold pieces of sorghum grains are provided as food for the larvae. The bold sorghum grains were ground in a home mill, producing pieces from each grain, and then heat-sterilised for 30 min at 100°C to eliminate any potential secondary infestations. Moreover, supplemented the material with 10 g of yeast to boost growth and 0.25 g/ kg of streptomycin sulphate to prevent bacterial infection. A mixture of 10 kg of sorghum with 400 g of raw, crushed groundnuts was stored in pre-sterilised wooden rearing boxes. A metal shelf supported the boxes in a set arrangement. The wooden box was secured with a lid and labelled with the date of inoculations noted. These boxes were maintained at a favourable temperature (28±2) degrees centigrade and relative humidity (75±5%). Each tray was inoculated with 0. 5 cc of Corcyra (0–1 h old) eggs to ensure the eggs were evenly dispersed within the food material. To stop larvae or moths from escaping, muslin cloth was covered these trays. The trays remained undisturbed for 30 days. Following 30 days, the moths were mechanically gathered using test tubes and transferred from each tray at 9:00 am to the specially designed oviposition cages. The moths were sorted into egg-laying cages made of plastic buckets where they had the opportunity to mate and lay eggs (20-litre capacities). Every morning, eggs were harvested and cleaned by rolling them on blotting paper to eliminate scales and other moth body parts. Cleaned eggs were also utilised for preserving the *Corcyra* culture and conducting various research activities.

Mass rearing of *Trichogramma* spp. on alternative host in India

Manisha *et al*. (2020) conducted a Study on alternative hosts for *Trichogramma* and analysed the production costs of *T. chilonis* on *Samia cynthia ricini* (Eri silkworm) compared to the rice moth. Their research revealed that cultivating *T. chilonis* on Eri silkworm eggs resulted in a higher benefit-cost ratio of 1.89, with a net profit of Rs. 4620, whereas rearing *T. chilonis* on *C. cephalonica* (rice moth) eggs yielded a benefit-cost ratio of 1.28 and a net gain of Rs. 2379. The study found that, for one hectare of land, a tricho-card made from Eri silkworm eggs containing 3500 eggs would produce approximately 35,000 to 40,000 adult *T. chilonis* individuals (9-10 adults per parasitised egg). In contrast, a trichocard made from rice moth eggs, with 16,000 to 17,000 eggs, would require 2-3 cards per hectare. Thus, the Eri silkworm proves to be a more viable and resource-efficient alternative host for rearing *T. chilonis* compared to the rice moth. This method offers cost-saving benefits and could support local Eri silkworm production, particularly benefiting tribal farmers and unemployed youth at the village level. Moirangthem *et al*. (2022) examined the effect of two host species and various trichocard colours on the parasitisation efficiency of *Trichogramma pretiosum* and *T. japonicum* in a controlled laboratory setting at 28 ± 2°C temperature and 75 ± 5% humidity. They assessed several biological parameters of both species reared on artificial hosts, *Corcyra cephalonica* and *Galleria mellonella*. The study found that *T. pretiosum* showed significant parasitism, with 85.33% on *C. cephalonica* and 72.67% on *G. mellonella*. *T. japonicum* parasitised *G. mellonella* eggs more effectively, with a rate of 72.33%, compared to 60.67% on *C. cephalonica*. To evaluate ovipositional preferences, they tested various trichocard colours (white, blue, yellow, purple, green, and red) for the two species. The results indicated that white and green trichocards were most suitable for the mass production of *Trichogramma* species. Gowda *et al.* (2021) explored the use of different factitious hosts for mass-rearing *Trichogramma japonicum*, a parasitoid employed in biological control worldwide. They compared the efficacy of three factitious hosts—*C. cephalonica*, *Ephestia kuehniella*, and *Sitotroga cerealella*—both in laboratory settings and in the field, specifically targeting the yellow stem borer (*Scirpophaga incertulus*) in rice. The study found that *T. japonicum* exhibited the highest

parasitism on *E. kuehniella* eggs, with the highest parasitoid emergence recorded from *S. cerealella* eggs (88.99% at 24 h). At 48 h, the highest emergence (94.66%) was noted from *E. kuehniella* eggs. Females emerging from *E. kuehniella* eggs also had significantly longer lifespans.

Climate-resilient strains of *Trichogramma:* development and applications

After storing *T. kashmirica* for 45 days at 6°C, Ahmad *et al.* (2011) examined the parasitism potential and cold storage response and found that the percentage of emergence and females fell from 96.0 to 60.6 and 88.3 to 86.8, respectively. The emergence of adults and the longevity of females showed a negative correlation, while the developmental period demonstrated a positive correlation with the length of the storage period. Prabhu *et al.* (2024) investigated temperature tolerance in five field strains of *Trichogramma chilonis* from the northern districts of Tamil Nadu. Their study revealed that laboratory strains of *T. chilonis* were significantly less effective in parasitisation and temperature tolerance compared to ecotypes collected directly from the field, likely due to continuous exposure to extreme temperatures. To identify a more temperature-tolerant ecotype for pest management, five field-collected strains were compared with the laboratory strain. These ecotypes, collected from sugarcane and citrus using the sentinel egg technique with *Corcyra cephalonica* eggs, were tested for their temperature tolerance. The results showed that all field-collected ecotypes exhibited higher emergence rates than the laboratory strain. At 15°C, the Chitteri ecotype had the highest emergence (83.44%), followed by Arungunam (78.65%) and Amirthapuram (75.57%). At 20°C, all ecotypes performed well, with the Chitteri ecotype again showing superior performance (95.66%) compared to others and the laboratory strain. At 35°C, while the laboratory strain and other ecotypes failed to develop, Chitteri and Arungunam ecotypes showed some development with adult emergence rates of 9.66% and 7.25%, respectively. Venkatesan and Jalali (2015) studied a Multiple Insecticide and High Temperature Tolerant Strain (MIHTTS) of *T. chilonis* and its effectiveness in controlling crop pests. They observed a significant reduction in the larval population of cotton bollworms in fields treated with MIHTTS of *T. chilonis*, where the parasitoid was released at 0.5 per plant, compared to the susceptible strain (0.8 per plant) and standard farmer practices (1.2 per plant). Additionally, there were more good open bolls and fewer bad open bolls, resulting in higher yields in MIHTTS-treated fields. This indicated that the tolerant strain was more resilient to insecticides and more effective at parasitising eggs in treated cotton fields. Similarly, in tomato fields, the tolerant strain showed a significant reduction in the larval population of *Helicoverpa armigera* when released at 50,000 ha-1, with 1.5 plants parasitised per plant, compared to the susceptible strain (4.8 plants per plant) and farmer practices (3.7 plants per plant). The MIHTTS also demonstrated higher egg parasitism and greater yields compared to the susceptible strain and farmer practices. The MIHTTS strain was also effective in controlling the diamondback moth in cabbage, showing a notable reduction in larval populations and higher parasitism rates, which contributed to a significant yield increase over the susceptible strain and farmer practices. This study suggested that the MIHTTS strain's superior performance was due to its tolerance to both insecticides and high temperatures in field conditions.

Improvement strategies for *Trichogramma* strains to enhance their efficacy in biological control

Jalali *et al.* (2006) studied the development of an Endosulfan-tolerant strain of *Trichogramma chilonis*, an egg parasitoid targeting lepidopteran pests. The laboratory-created strain was exposed to progressively higher concentrations of endosulfan, starting from a sub-lethal dose (0.004%) to the field-recommended concentration (0.09%). After 341 generations of continuous exposure, the strain developed tolerance, with an LC50 value of 1074.96 ppm, compared to 70.91 ppm for the susceptible strain. Genetic studies revealed a semi-dominant inheritance of tolerance, with a dominance degree (D) of 0.58. The resistant factor of the tolerant strain was 15.1 times higher than the susceptible strain, while the F1 crosses showed a factor of 8.53. Under net house conditions, the tolerant strain successfully parasitised 56% of *Helicoverpa armigera* eggs on cotton plants right after insecticide spraying, compared to just 3% parasitism by the susceptible strain. The high survival rate of immature stages in the tolerant strain demonstrated its ability to withstand insecticide exposure. However, tolerance broke down after four generations without insecticide exposure. The tolerant strain was recommended for use in bio-intensive Integrated Pest Management (IPM) programs, especially in crops with heavy insecticide use. In a related study, *Trichogramma chilonis* was also bred for temperature tolerance. Srivastava *et al.* (2015) developed a strain of *T. chilonis* capable of withstanding high temperatures in a biological control laboratory at IARI (PUSA), New Delhi. The researchers analysed the parasitoid's biological characteristics, including fecundity, emergence rates, and survivability at different temperatures (25, 27, 29, and 31ºC). The highest fecundity and emergence rates were observed at 27ºC, with increases of 107.23% in fecundity, 184.50% in emergence, and 15.65% in female survival from the baseline to the 35th generation. However, male survival and female population showed slight declines (8.2% and 1.2%, respectively). They found that the resilience of the immature stages in this temperature-tolerant strain demonstrated their

ability to endure higher temperatures, making it suitable for use in warmer environments.

Promoting *Trichogramma* as biocontrol: recent efforts and challenges in India

Pawar *et al.* (2023) studied ways to enhance the biocontrol potential of *Trichogramma chilonis* against borer pests in wheat and chickpeas. Plants release Herbivore-Induced Plant volatiles (HIPVs) in response to herbivore attacks, which serve to attract the natural enemies of the herbivores. Applying these effective HIPVs in controlled release formulations in the field can attract both released and wild parasitoids, thereby increasing their search time for various stages of herbivores and improving pest management. A gel made of octadecane, a saturated hydrocarbon, was put on wheat and chickpeas 24 h after *Trichogramma chilonis* was released. This made the plants more resistant to the pink stem borer (*Sesamia inferens*) and the pod borer (*Helicoverpa armigera)*.This led to reduced pest damage and higher grain yields. Using controlled-release formulations of effective plant volatile organic compounds (pVOCs) can thus boost the foraging activity of natural enemies, improving the control of crop herbivores. Baskaran *et al.* (2024) conducted a study on the Yellow Stem Borer (YSB), *Scirpophaga incertulas* (Walker), a major pest of lowland rice (*Oryza sativa L.*) that causes significant yield losses of 30–40%. Biological control methods, including the inundative release of the egg parasitoid *Trichogramma japonicum* Ashmead, have been used to manage YSB populations across Asia. However, there is limited information on the optimal timing and frequency of parasitoid releases for controlling YSB in summer lowland rice. To address this gap, an experiment was carried out at ICAR-National Institute of Biotic Stress Management in Raipur, Chhattisgarh, during the summer seasons of 2018 and 2019. The study aimed to determine the best timing and number of releases of *T. japonicum* for effective biological control of YSB. The experiment included four treatment schedules: T1, which involved four releases of *T. japonicum* at weekly intervals on the 7th, 14th, 21st, and 28th Days After Planting (DAT); T2, with releases on the 14th, 21st, 28th, and 35th DAT; T3, with releases on the 21st, 28th, 35th, and 42nd DAT; and T4, the control group with no parasitoid releases. The results showed that the T2 schedule, which included four releases of *T. japonicum* at a rate of 50,000 wasps per hectare per release, significantly reduced YSB-induced damage. In the summer of 2018, this treatment led to a 45.83% reduction in dead heart (from 16.8% in the control to 9.1%) and a 47.05% reduction in white ear (from 3.4% in the control to 1.8%). Similarly, in summer 2019, T2 treatment reduced dead heart by 43.35% and white ear by 46.15% compared to the control. These reductions in YSB damage corresponded with increased grain yields in T2-treated plots, showing a yield increase of 12.74–20.18% across the two years. The findings suggest that the T2 release schedule offers an ecologically sustainable approach to controlling YSB in summer lowland rice. They also studied native *Trichogramma* species for sustainable pest management, focusing on the comparative parasitic activity of three native *Trichogramma* species. The species studied included *T. chilonis* from rice (Balloda Bazar), *T. chilonis* from maize (Kanker district), and *T. japonicum* from NBAIR, Bengaluru. The results revealed that *T. japonicum* from farmer fields exhibited the highest parasitic activity at 86.4%, followed closely by the NBAIR strain at 82.3%. Among the *T. chilonis* strains, the one from NBAIR had the highest parasitic activity at 76.9%, while the two native populations showed parasitic activities of 71.1% and 66.4%, respectively. They also optimised *T. japonicum* release schedules for controlling the rice yellow stem borer during the kharif season. They tested three release schedules of *T. japonicum* at a rate of 50,000 wasps per hectare, with four releases on the 32nd, 39th, 46th, and 51st days after transplanting. This schedule resulted in a 54.7% reduction in dead heart symptoms and a 66.1% decrease in white ear symptoms, along with the highest grain yield of 6.01 tonnes per hectare. In a different study, they looked at how well different kairomone gel mixtures worked at increasing the biocontrol potential of *T. chilonis* against the chickpea pod borer. Chickpea plots treated with octadecane gel formulations at 200 ppm and 500 ppm significantly reduced the average number of pod borer larvae, showing reductions of 34.28% (30.24 larvae per 10 plants) and 35.99% (29.45 larvae per 10 plants), respectively. In plots where only *T. chilonis* was released, the combination of PSB in octadecane 500 ppm and *T. japonicum* treatment increased wheat grain yield by 25.06% compared to a 10.30% increase in wheat plots with only wasp releases. Field trials of the kairomone gel formulation in chickpeas showed a 17.69% reduction in larval population (37.87 larvae per 10 plants) compared to 46.04 larvae per 10 plants in the control plots. The application of the octadecane gel at 500 ppm combined with *T. chilonis* release reduced pod damage by 31.22%, resulting in only 10.20% pod damage, while the *T. chilonis*-only plots showed 15.64% pod damage and control plots had 14.83%. The chickpea grain yield in plots treated with the octadecane gel at 500 ppm and *T. chilonis* increased by 14.41%, compared to an 8.76% increase in plots with only *T. chilonis* releases (Baskaran, 2022). Lalitha *et al.* (2023) investigated the field effectiveness of *T. chilonis* reared on different factitious hosts for managing sugarcane stem borers. *T. chilonis* is commonly mass-reared on *C. cephalonica* eggs, but in this study, eggs from two alternative hosts, the eri silkworm (*Samia cynthia ricini*) and *C. cephalonica*, were used. The performance of *T. chilonis* reared on these two hosts was assessed against sugarcane borers *Chilo infuscatellus* and

Chilo sacchariphagus indicus. Weekly released *T. chilonis* from both host species resulted in comparable parasitism rates and successfully reduced crop damage. No significant difference was observed in parasitism levels (10.53% for *S. cynthia ricini* and 7.81% for *C. cephalonica*). Additionally, the percentage of millable canes was higher in fields with parasitoid releases compared to control fields. Using *S. cynthia ricini* eggs reduced the cost of rearing *T. chilonis* by 50%, making it more cost-effective for on-farm production, while *C. cephalonica* eggs remain suitable for commercial insectaries and research institutes.

FUTURE PROSPECTS AND NEEDS

The future of *Trichogramma* as a biocontrol agent in India is promising due to its potential for sustainable pest management. However, several key areas need attention to fully realise their benefits:

Expansion of research and development

It is essential to conduct ongoing research on the biology, ecology, and genetic enhancement of *Trichogramma* species. The utility of *Trichogramma* will be increased by the development of climate-resilient strains and the improvement of its adaptability to a variety of agroecological zones in India.

Integration with other pest management practices

Combining *Trichogramma* with other biocontrol agents, chemical controls, and cultural practices will be essential for IPM strategies. This holistic approach can help improve pest control efficacy and reduce the dependence on chemical pesticides.

Mass production and distribution

Efficient mass-rearing techniques and cost-effective production systems need to be scaled up for widespread application. Establishing local production centres and improving the distribution network will make *Trichogramma* more accessible to farmers.

Farmer awareness and training

Enhancing awareness about the benefits of *Trichogramma* and providing training to farmers on its application and integration into pest management systems is vital. Extension services and farmer-field schools can play a pivotal role in promoting its use.

Policy support and funding

Government policies and financial support are essential to encourage the adoption of *Trichogramma*-based biocontrol programs. Incentives for organic farming, as well as subsidies for biocontrol agents, can accelerate the adoption of *Trichogramma* in pest management.

Long-term monitoring and impact assessment

Conducting long-term studies to assess the ecological impact and cost-effectiveness of *Trichogramma* in different cropping systems will help refine its use. Data on its success in pest control, impact on non-target organisms, and sustainability will guide future strategies.

CONCLUSION

Over the past 25 years, *Trichogramma* species have shown significant success in controlling pests in various agricultural ecosystems, including commercial cash crops, vegetables, fruit orchards, and even certain forest plantations. The results have been particularly impressive against lepidopteran leaf feeders and borers. *Trichogramma* plays a key role in IPM, offering a comprehensive approach to pest control in an eco-friendly manner. As agriculture moves towards more sustainable practices, *Trichogramma* will become an increasingly important component in reducing chemical pesticide use, protecting ecosystems, and ensuring food security.

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