HYMENOPTERAN PARASITOIDS: DIVERSITY, HOST ASSOCIATIONS AND BIOCONTROL IMPLICATIONS IN WEST BENGAL, INDIA

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Abstract: Hymenopteran parasitoids constitute one of the most diverse groups of natural enemies regulating insect populations. This article reviews current knowledge about the diversity and host associations of hymenopteran parasitoids and the role played by these parasitoids in biological control practices in West Bengal, India. Different agroclimatic zones in the state favour the occurrence of different parasitoids from families such as Braconidae, Ichneumonidae, Trichogrammatidae, and Eulophidae, which have been reported in association with various major pests in ecosystems including rice, vegetables, fruits, and tea. Interactions between hosts and parasitoids occur within a complex food web. Although there are many opportunities for biological control through augmentation and conservation methods, several factors, such as the excessive use of pesticides, pose challenges.

Keywords- **Hymenoptera, Parasitoids, Biocontrol, Natural enemies, Insect pest management.**

1. Introduction

Parasitoids are organisms, mostly insects that live either inside or outside their hosts and ultimately kill them during their own life cycles. Since their activities and life-cycle events are timed with the most favorable periods for pests, parasitoids are highly effective biological control agents (Kumaraswamy et al., 2024). Parasitoids are of great significance to the conservation and stability of agroecosystems since they assist in restoring and maintaining ecological equilibrium among pest populations. They cause density-dependent mortality, providing stability to host–parasitoid systems. Parasitoids contribute to population stability through the density dependence of the host (Hassell, 2001). Parasitoids participate in co-evolutionary interactions with their hosts. Parasitoids are excellent candidates for studies on host–parasite co-evolution (Henter, 1995). In Hymenoptera, the superfamilies Ichneumonoidea and Chalcidoidea represent the largest groups of parasitoids, with impressive diversity in host specificity, life history, and behavior (Heraty et al., 2011). Parasitoids are crucial players in terrestrial ecosystems, imposing substantial top-down pressure on arthropod hosts while forming the basis for many biological control programs employed globally (Moreau & Asgari, 2015). As one of the most diverse insect functional groups, parasitoid Hymenoptera attack hosts from a wide range of arthropod lineages and environmental settings, thus occupying pivotal roles within food webs (Hamback et al., 2024). Contemporary reviews demonstrate that differentiation in host ecological specialization and evolutionary innovations have served as primary drivers of parasitoid diversification, providing explanations for their exceptionally high diversity (Hamback et al., 2024). Complementary research in comparative genomics is revealing insights into the genetics of host specificity, venom evolution, chemo-sensation, and life history of parasitoid wasps, offering novel avenues for both evolutionary studies and practical applications in entomology (Ye et al., 2024). The complexity of both physiology and behavior involved in host–parasitoid interactions is also highlighted by current studies, which include adaptive manipulation of hosts as well as dynamic ecological feedback involved in structuring community assembly (Fei, Gols & Harvey, 2023). New research on parasitoid-associated microbiomes indicates another factor that could influence parasitism success, host immune responses, and adaptation to different environments (Gomez-Govea et al., 2024). Global warming is considered one of the major factors influencing parasitoid distribution, phenological synchrony, and the efficacy of biological pest control efforts (Aguila et al., 2023). Parasitoid wasps form a significant portion of global insect biodiversity, and current studies indicate that host shifting and trophic specialization are two factors responsible for the rapid rate of parasitoid evolution (Forbes et al., 2018). Phylogenetic studies of Hymenoptera have shed light on the evolution of parasitoids, identifying multiple independent origins of parasitism as well as transitions from ecto-parasitism to endo-parasitism (Branstetter et al., 2017; Peters et al., 2017). Integrative taxonomy, which combines DNA barcoding with morphological characterization, has facilitated the identification of cryptic species diversity among parasitoids, notably in chalcidoids and braconid subfamilies (Powell, 2018).

2. Study Area: West Bengal, India

West Bengal is a state of India. It is located in the eastern part of the country. West Bengal stands out as a Biogeographical transition zone that stretches from the eastern Himalayas to the Bay of Bengal. It occupies an area of 88,752 Square kilometers. The state borders Bangladesh to the east and has common boundaries with Nepal, Bhutan, and Indian states like Sikkim, Assam, Bihar, Jharkhand, and Odisha. West Bengal's geographical location makes it ideal for biodiversity research involving hymenopteran parasitoids.

3. Physiography and Landscape Diversity

There is immense physiographical diversity in the state varying from the Himalayan hills (Darjeeling district) to the Gangetic alluvial plain and the coast mangroves of the Sundarbans. The central zone represents fertile Gangetic alluvial planes and the northern zone consists of laterite upland zone with undulating landscapes. Sundarbans is in the southern zone. Sundarbans zones falls within the Ganges Delta being the largest mangrove ecosystem in the world. The northern zone has mountainous landscape followed by the physiographic zones of Terai and Dooars comprising alluvial floodplains. These kind of physiographical diversity leads to diverse ecological habitats which play an important role in shaping the diversity of insects, host plants and distribution pattern of parasitoids.

4. Climate

There are many variation observed in the climate of West Bengal it has tropical Savannah in the southern portion of the state to humid subtropical areas in the north. Four prominent seasons occur in the region, these are summer, monsoon, post monsoon (autumn) and winter. The maximum temperature during the summer months can range between 38-45°C Winters are mild in the plains 15°C and colder in the Himalayan region. Southwest monsoon from June to September accounts for the large scale of precipitation. It plays an important role in determining the climate condition especially affecting agricultural ecosystems and the insect community of West Bengal.

4.1 Agro-Climatic Zones and Agricultural Systems

West Bengal can be classified into six main agro-climatic regions depending upon differences in rainfall, soil, topography. These are (1) Northern hill region, (2) Terai-Teesta alluvial region, (3) Gangetic alluvial, (4) Vindhyan alluvial region, (5) Undulating red laterite region, (6) Coastal salt region (Mandal et al, 2022). Agriculture is the predominant form of land utilisation. It includes many kinds of crops like paddy, jute, tea, vegetables, pulses, oil seeds etc Different cropping system offer various types of host insects, thus ensuring abundant parasitoids.

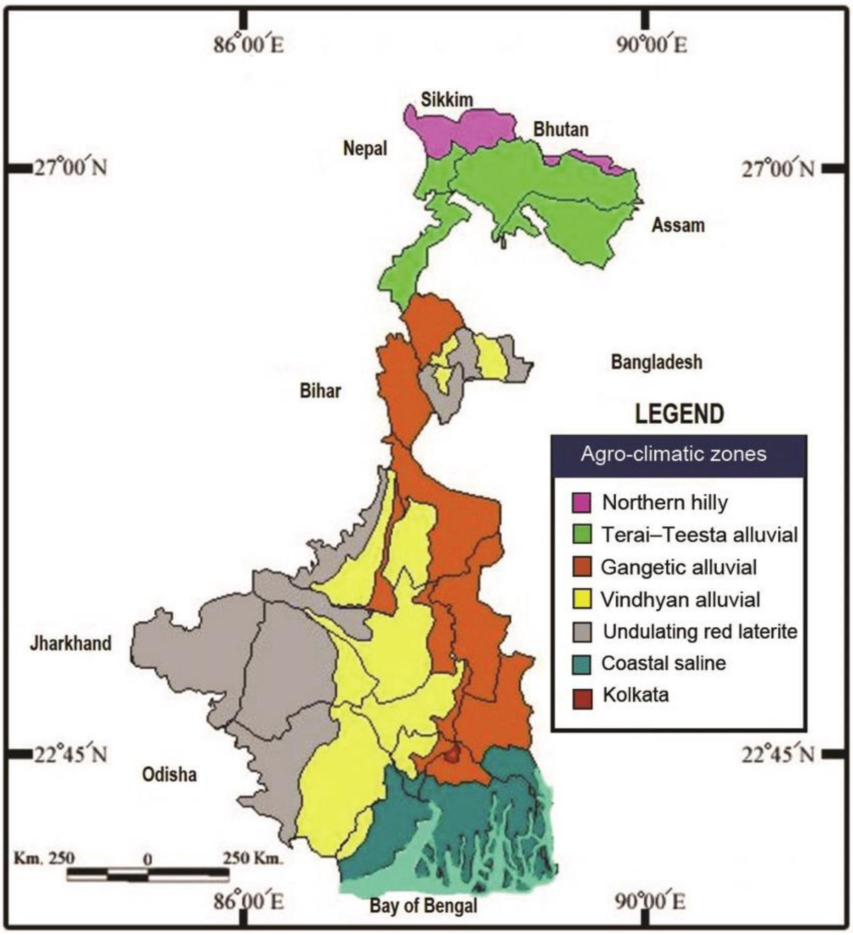

fig. 1. map showing six different agro-climatic zones of west bengal, india.

5. Biodiversity and Ecological Significance

West Bengal is rich in ecological significance. It includes many forests, wetlands, crop fields, and mangroves harbors an abundance of fauna. The Sundarbans delta constitutes a distinct ecosystem that is productive in terms of biomass and food chains. Sundarbans delta marked by tidal water systems and mangroves. The Forest and agricultural environments in West Bengal form part of the heterogeneity of the environment. Thus providing suitable habitats of parasitoids. These conditions together with the practice of intensive agriculture in West Bengal, make West Bengal ideal for parasitoid biodiversity and research on biocontrol of parasitoids.

5.1 Relevance to Parasitoid Diversity Studies

Ecological diversity, variation in climate condition and heterogeneity make West Bengal one of the best regions to study the hymenopteran parasitoids diversity. The presence of different pests along with high plant diversity and ecological diversity helps in creating condition that support both specialist and generalist parasitoids. Anthropogenic activities such as excessive use of pesticides, farming and other activities can also have an impact on parasitoid population dynamics. Ecological and agro climatic heterogeneity of West Bengal create an interesting setting to explore the diversity of parasitoids and their relationship with host plants.

5.2 Hymenopteran Parasitoids in West Bengal

Table 5.2: the following table represents major hymenopteran parasitoid species reported from west bengal

Common Name	Scientific Name	Family	Associated host	Reference
Eulophid parasitoid wasp	*Tetrastichus epilachnae*	Eulophidae	The Giant Ladybird Beetle (*Anisolemnia dilatata*)	Pal et al., 2022
Eulophid parasitoid wasp	*Chrysonotomyia postmarginaloides*	Eulophidae	*Mangifera indica*	O'Loughlin et al, 2024
Eulophid parasitoid wasp	*Pseudosecodes calicuticus*	Eulophidae	*Mangifera indica*	Kumar et al, 2012

Eulophid parasitoid wasp	*Elachertus nigrithorax*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Elasmus punensis*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Elasmus anticles*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Hemiptarsenus varicornis*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Sympiesis striatipes*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Aprostocetus bangaloricus*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Aprostocetlls benazeer*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Aprostoeetus dala*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Aprostoeetus kuriani*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Aprostocetus ricosus*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Aprostocetlls vatiata*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Leptocybe invasa*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Neotrichoporoides curiosus*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Neotrichoporoides galia*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Neotrichoporoides idukkiensis*	Eulophidae	*Mangifera indica*	Kumar et al, 2012
Eulophid parasitoid wasp	*Neotrichoporoides viridimaculatus*	Eulophidae	Dipteran insects	Kumar et al, 2012
Eulophid parasitoid wasp	*Tetrastichus dulcicuilis*	Eulophidae	Lepidoperan and Coleopteran insects	Kumar et al, 2012
Egg parasitoid wasp	*Trichogramma chilonis*	Trichogrammatidae	Eggs of *Corcyra cephalonica* and other lepidopteran pests	Saha et al., 2017
Larval ectoparasitoid wasp	*Bracon brevicornis*	Braconidae	Larvae of *Corcyra cephalonica* and several lepidopteran pests	Saha et al., 2017

Egg parasitoid	*Telenomus cf. remus*	Scelionidae	Eggs of fall armyworm *Spodoptera frugiperda*	Liao et al., 2019
Larval endoparasitoid	*Microplitis manila*	Braconidae	Larvae of *Spodoptera frugiperda*	Lu et al., 2025
Larval endoparasitoid	*Microplitis prodeniae*	Braconidae	Larvae of *Spodoptera frugiperda*	Yang et al., 2018
Egg- larval parasitoid	*Chelonus formosanus*	Braconidae	Larvae of *Spodoptera frugiperda*	Pal et al., 2024
Larval parasitoid	*Cotesia ruficrus*	Braconidae	Caterpillars of Lepidoptera including Spodoptera spp.	Pal et al., 2024
Larval endoparasitoid	*Campoletis chloridae*	Ichneumonidae	Larvae of *Helicoverpa armigera* and *Spodoptera frugiperda*	Pal et al., 2024
Larval parasitoid	*Charops bicolor*	Ichneumonidae	Lepidopteran caterpillars	Pal et al., 2024
Larval ectoparasitoid	*Euplectrus* spp.	Eulophidae	Larvae of *Spodoptera frugiperda*	Pal et al., 2024
Hyperparasitoid wasp	*Nesolynx banabitanae*	Eulophidae	Parasitoid *Charops aditya* (host via butterflies *Ariadne merione*, *Elymnias hypermnestra*)	Chakrovorty et al., 2025
Egg parasitoid wasp	*Trichogramma japonicum*	Trichogrammatidae	Eggs of rice stem borers	Irshad et al., 2025
Egg parasitoid wasp	*Trichogramma chilonis*	Trichogrammatidae	Eggs of *Helicoverpa armigera*, *Corcyra cephalonica*	Pal et al., 2024
Egg parasitoid	*Telenomus remus*	Scelionidae	Eggs of *Spodoptera frugiperda*	Pal et al., 2024
Egg parasitoid	*Trissolcus basalis*	Scelionidae	Eggs of pentatomid bugs	Lahey et al., 2023
Spider egg parasitoid	*Idris* spp.	Scelionidae	Spider egg sacs	Rajmohana et al., 2025
Larval parasitoid	*Microplitis manila*	Braconidae	*Spodoptera frugiperda* larvae	Pal et al., 2024
Larval parasitoid	*Microplitis prodeniae*	Braconidae	*Spodoptera frugiperda*	Pal et al., 2024
Egg-larval parasitoid	*Chelonus formosanus*	Braconidae	*Spodoptera frugiperda*	Pal et al., 2024

Larval parasitoid	*Cotesia ruficrus*	Braconidae	Lepidopteran caterpillars	Pal et al., 2024
Larval parasitoid	*Campoletis chlorideae*	Ichneumonidae	*Helicoverpa armigera,* FAW	Pal et al., 2024
Larval parasitoid	*Charops bicolor*	Ichneumonidae	Lepidopteran larvae	Pal et al., 2024
Larval parasitoid	*Charops Aditya*	Ichneumonidae	Butterfly larvae	Pal et al., 2024
Larval parasitoid	*Trathala flavoorbitalis*	Ichneumonidae	*Leucinodes orbonalis*	M. Ranjith et al., 2020
Larval parasitoid	*Temelucha* spp.	Ichneumonidae	Lepidopteran larvae	S. Anandhi and VR Saminathan, 2021
Larval ectoparasitoid	*Euplectrus* spp.	Eulophidae	Caterpillars *(Spodoptera)*	Pal et al., 2024
Hyperparasitoid	*Nesolynx banabitanae*	Eulophidae	Parasitoid *Charops aditya*	Chakrovorty et al., 2025
Pupal parasitoid	*Brachymeria lasus*	Chalcididae	Lepidopteran pupae	Peng et al., 2025
Pupal parasitoid	*Dirhinus giffardii*	Chalcididae	Dipteran pupae	Maquart et al., 2020

5.3 Host Associations in West Bengal Agroecosystems

In West Bengal, the interactions between host and parasitoid are largely determined by agro-climatic zones prevailing in the state. Specially, those concerned with rice, jute, vegetable crops tea, fruits etc. Various hymenopteran parasitoid species have been identified that attack significant agricultural pests.

5.3.1. Rice Ecosyatem

There are diverse parasitoids communities in rice fields that affect important Lepidoptera pests. For examples, parasitoids of eggs include *Trichogramma japonicum, Trichogramma chilonis,* are used in biological control to combat lepidopteran pest like *Scirpophaga incertulas* (stem borer), *Cnaphalocrocis medinalis* (leaf folder) in crops like sugar cane, rice frequently utilised in India.

5.3.2. Vegetable Crops

The ecosystems found within vegetable crops (example: brinjal, cabbage, tomato), house parasitoids such as *Diadegma semiclausum*, which parasitize the diamondback moth *(Plutella xylostella),* a significant pest within the crucifers (Momanyi et al., 2006). *Bracon hebetor* (braconid parasitoids) is commonly found by parasitoid, frequently recorded attacking lepidopteran larvae in stored products and field crops.

5.3.3. Fruit Ecosystems

Fruits like mango and guava from south and central parts of West Bengal, serve as pest for parasitoids of dipteran pests including fruit flies *Bactrocera* spp. Opiine braconoid wasps parasitize the eggs and larvae of fruit flies, leading to reduced pest infestations (Clarke et al, 2021).

5.3.4. Tree Plantations

The parasitoids *Apanteles* species and Eulophids are found along with tea pests like caterpillars and leaf miners in the Darjeeling and Dooars tea ecosystem areas. The parasitoids play an important role in pest control in a fairly low pesticide environment (Pandya et al., 2024).

5.3.5. Aphid and Whitefly Systems

Vegetable crop pests and mustard belonging to the Hemiptera order usually have parasites like *Aphidius colemani* and *Diaeretiella rapae braconids*, which form typical "mummies" of aphids. Parasitoids within the chalcidoid group, *Encarsia* spp., and Eulophids are linked to the whitefly (*Bemisia tabaci)* (Liu et al., 2014).

5.3.6. Host Relationships

The parasitoids of the Hymenoptera order demonstrate an impressive variety of host relationships by targeting different groups of arthropods especially those of the insect order Lepidoptera, Hemiptera, Coleoptera, Diptera. Typically these parasitoids develop inside the body of their hosts (endoparasitoids) or outside (ectoparasitoids). Eventually resulting in the death of host organism. The criteria that distinguishes parasitoids from other parasites (Rózsa & Garay, 2023). Parasitoids within the West Bengal agro-ecosystem, mainly include Braconid and ichneumonid parasitoids, which prefer Lepodopteran larvae as hosts. Chalcidoid parasitoids, including members of the families Eulophidae and Encyrtidae, often parasitize hemipteran such as aphids, whiteflies etc. The host parasitoid relationship in parasitoids can vary from exclusive specialisation (monophagy) to generalisation (polyphagy), depending on evolutionary and ecological factors. Behavioral ecology is equally important in host exploitation. Female parasitoids typically show stage dependent host choice when distributing hosts for egg laying and host feeding. Thus maximising their reproductive fitness and longevity. Density dependent interplay between the host and parasitoid populations governs population dynamics as explained in classical host-parasitoid theory (Nicholson-Bailey model) which emphasizes oscillations in population size and stability criteria. Hyperparasitoids target the primary parasitoids and may affect the efficiency of biological control. Environmental influences including habitat complexity, human intervention, climate etc. have impacts on these systems as well.

5.4. Host Associations and Trophic Relationships

Table 5.4: parasitoid species with diverse host associations

Parasitoid species	**Family**	**Host insect**	**Host crop/ ecosystem**	**Host stage attacked**	**Region (WB)**	**Reference**
Trichogramma japonicum	Trichogrammatidae	*Scirpophaga incertulus*	Rice	Egg	Gangetic plains	Irshad et al, 2025
Trichogramma chilonis	Trichogrammatidae	*Helicoverpa armigera*	Vegetables	Egg	Statewise	Pal et al., 2024
Telenomus remus	Scelionidae	*Spodoptera frugiperda*	Maize	Egg	Birbhum	Pal et al. (2024)
Cotesia flavipes	Braconidae	Stem borers	Rice	Larva	South Bengal	Lv et al., (2011)
Cotesia marginiventris	Braconidae	*Spodoptera* spp.	Maize	Larva	WB plains	Rameshkumar et al., 2024
Microplitis manilae	Braconidae	*Spodoptera frugiperda*	Maize	Larva	Multiple districts	Pal et al. (2024)
Microplitis prodeniae	Braconidae	*Spodoptera* spp.	Maize	Larva	Malda	Pal et al. (2024)
Chelonus formosanus	Braconidae	*Spodoptera frugiperda*	Maize	Egg-larva	Birbhum	Pal et al. (2024)
Campoletis chlorideae	Ichneumonidae	*Helicoverpa armigera*	Pulses	Larva	WB plains	Pal et al. (2024)
Charops bicolor	Ichneumonidae	FAW larvae	Maize	Larva	Multiple districts	Pal et al. (2024)
Temelucha spp.	Ichneumonidae	Lepidopteran larvae	Crops	Larva	Murshidabad	Pal et al. (2024)

fig. 2. braconidae, a highly diverse family of hymenopteran parasitoids in west bengal, india. (Source: https://war.wikipedia.org/wiki/Braconidae)

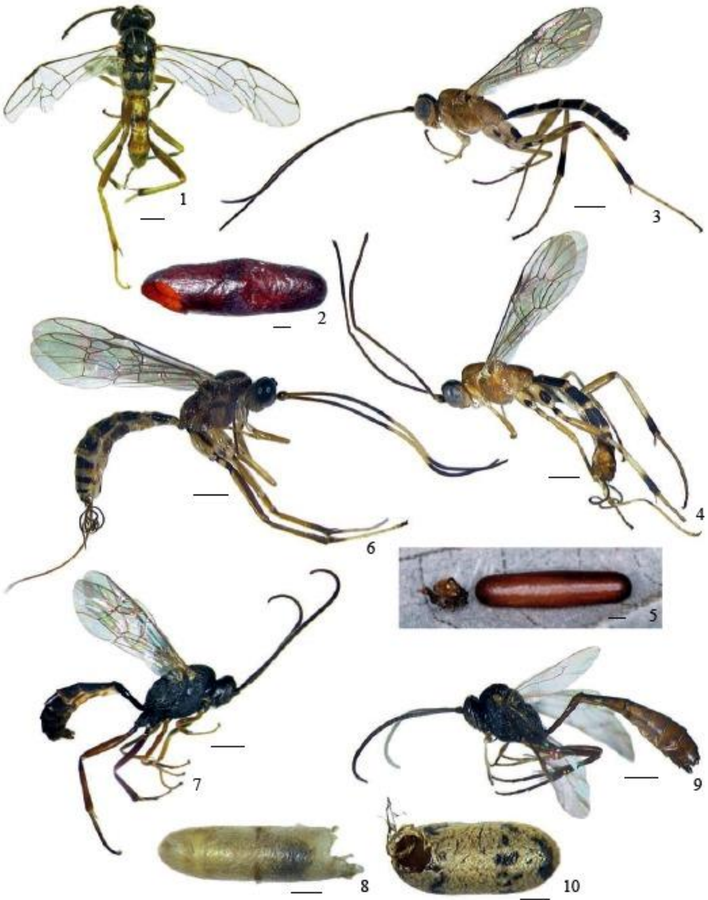

fig. 3. ichneumonidae parasitoids. 10. ichneumonidae. 1-6, banchinae. 1-2, *Diradops* sp. (Source: Fernandes et al. 2010)

fig. 4. scelonidae parasitoids (source: https://alchetron.com/Scelionidae)

6. Role of Hymenopteran Parasitoids in Biological Control

Hymenopteran parasitoids form a very significant group of natural enemies responsible for controlling the insect pest population. The capability of these parasites to parasitize and finally eliminate their hosts ensued their efficiency in reducing the population of agriculturally important pests, especially in tropical agricultural ecosystems (Örgen & Gülmez, 2024).

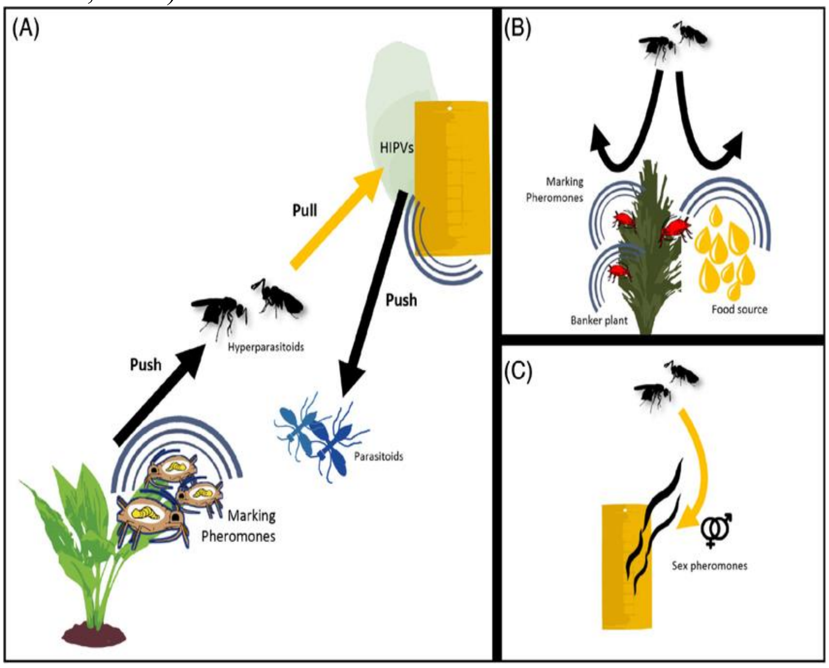

fig. 5. hyperparasitoids are essential to maintaining a balance, in crop ecosystems. (source: Harvey et al, 2019)

6.1. Natural Biological Control

Parasitoids act as regulators for ecological equilibrium by exercising density dependence control over the hosts. Braconidae and Ichneumonidae parasitize the larva of Lepidopteran pests. Trichogrammatidae parasitize eggs. Egg parasitoids *Trichogrreamma japonicum* reduce the infestation rates of stem borers in rice fields through parasitization of eggs prior to hatching into larvae (Tazerouni et al., 2019).

6.2. Applied Biological Control Strategies

Parasitoids are used to a great emphasis in all the three biological control practices, e.g., classic al, augmentative, conservation biological controls. Parasitoids at the larval stage, like *Cotesia flavipes,* used against stem borers in cereals (Polaszek, Walker., 1991).

6.3. Role in Integrated Pest Management (IPM)

Parasitoids play an important role of IPM implementation programs by minimal usage of chemical insecticides and improving environmental sustainability. They are highly host-specific biocontrol agents. They reduce the number of pests surviving to the next generation. Pests targeted by parasitoids perish more gradually than prey of predators, which are instantly killed or rendered ineffective. Even though some hosts become incapacitated, others could keep eating or perhaps even lay eggs eventually they pass away. Compared to many predators, parasitoids frequently complete their lives more promptly and multiply more rapidly (Prakash, 2010). When creating a biological control programme that uses this variant of the parasitoid in field settings, this finding must be taken into consideration (Bueno et al., 2009).

fig. 6. images of some common parasites/pests (centre cycle) and biological control agents (external cycles) used in the biocontrol of parasites. (source: cusumano et al. 2019)

6.4. Ecological and Economic Significance

Bees are the important pollinators of both flowering plants and agricultural crops ensuring plant reproduction and food production (Khalifa et al., 2021). Parasitoid wasps manage insect populations. Effective utilization of parasitoids helps to reduce the insecticide applications, resulting in more sustainable agricultural systems (Haas-Renninger, 2024).

7. Hymenopteran Parasitoid Study Techniques

Several techniques have been employed in the investigation of hymenopteran parasitoids. These techniques are as follows:-

7.1. Field Parasitoid Sampling Methods

Various techniques have been developed for conducting field sampling, these are Sweep net, yellow pan trap, light trap, and Malaise trap are common tools used for collecting adult parasitoids (Mukundan & Rajmohana, 2018). Malaise trap proves to be most efficient in trapping flying hymenopterans. The yellow pan trap works well in collecting smaller parasitoids like Chalcidoids.

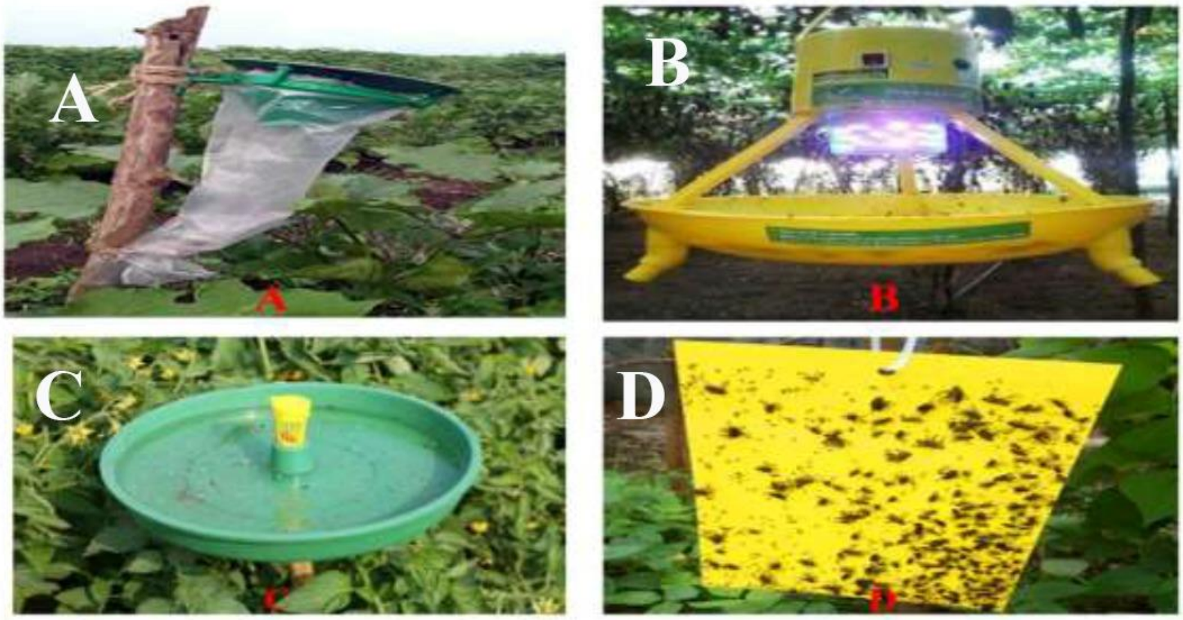

fig. 7. showing types of insect traps: a. pheromone trap, b: light trap, c: water trap, d: yellow sticky trap biological pest control. (source: https://www.researchgate.net/figure/figure-showing-types-of-insect-traps-a-pheremone-trap-blight-trap-cwater-trap_fig2_362429687)

7.2. Parasitoids' Hosts Rearing and Laboratory Experiments

Parasitoids are reared on collected insects that may be eggs, larvae, or pupae kept in laboratory conditions until the emergence of parasitoids. Such a technique facilitate the determination of preferred stages of hosts and rates of parasitism and other life history characteristics.

7.3. Molecular Methods

The application of molecular methods, e.g., DNA barcoding through mitochondrial cytochrome c oxidase I (COI) gene sequencing, gain increasing relevance in parasitoid biology. The benefits of using these methods include facilitating species recognition, identifying cryptic species, determining phylogenetic affiliation (Panprommin et al., 2019). The molecular methods can be applied to establish associations between hosts and parasitoids.

7.4. Ecological and Statistical Methods

Statistics is used to determine parasitoid diversity, community composition, density. Shannon-Wiener Index, Simpson's Index, parasitization frequency computed to study ecological trends. Models like the Nicholson-Bailey model are frequently used to stimulate host-parasitoid interactions and population control (Hassell, 2000).

7.5. Spatial and GIS-based Analysis

Geographic Information System (GIS) can be described as the ability to manipulate spatial data into different forms and extract additional meaning as a result. For disease epidemiology at an exploratory level, GIS is well suited for the study of associations between location, disease, vector, environment due to its display capabilities (Simoonga et al., 2009).

8. Comparative Population Dynamics and Percentage of Hymenopteran Parasitoids

8.1 Comparative Population Dynamics of Hymenopteran Parasitoids

Table 8.1: comparative studies on the population dynamics of hymenopteran parasitoids

Parameter	Global context	Indian context	West Bengal context
Species Diversity	Parasitoid wasps constitute one of the most diverse insect groups, representing a major portion of	High diversity across agroecosystems (e.g., >40 species recorded in crop systems (Darshan R & J. N. Hegde, 2024).	High but underexplored diversity; new species and associations still being documented (Chakraborty et al, 2025).

	Hymenoptera diversity (Polazek & Vilhemsen, 2023).		
Population Pattern	Oscillatory or cyclic dynamics governed by host–parasitoid interactions and spatial processes (stable/unstable equilibria) (Hassell et al, 1991)	Strong seasonal fluctuations linked to cropping cycles and climate (Daniel et al, 2019).	Strongly seasonal peaks (kharif) synchronized with pest outbreaks in rice-based systems (Dutta et al, 2024).
Host - Parasitoid Regulation	Density-dependent parasitism regulates host populations; functional responses (Type II/III) influence stability (Ferna ́ndez-arhex & Corley, 2003).	Natural enemies (including parasitoids) significantly contribute to pest mortality in crop ecosystems (Chaitanya et al, 2024).	Multiple parasitoid species attack different life stages (egg & larval), enhancing regulations of pests like fall armyworm (Pal et al., 2024).
Climate Influence	Temperature and seasonality strongly affect phenology and interaction stability (Lu et al., 2024).	Rainfall, humidity, and temperature drive population build-up and decline (Emana GD, 2007).	Monsoon-driven agroecosystems determine timing of parasitoid peaks and activity (Swapna Rani et al, 2023).
Parasitism Rates	Can stabilize or destabilize host populations depending on functional response and spatial heterogeneity (Ferna ́ndez-arhex & Corley, 2003).	Significant parasitism levels observed (Chaitanya et al, 2024).	High parasitism potential due to multiple species complexes in agro-ecosystems (Pal et al., 2024).
Biological Control Role	Widely used in classical and augmentative biological control programs (Plouvier & Wajnberg, 2018).	Increasing adoption in IPM programs (e.g., egg parasitoids in crops) (Kumarswamy et al, 2024).	High potential for sustainable pest control (Pal et al., 2024).
Population Stability	Stability enhanced by spatial heterogeneity and Type III functional response (Cordoleani et al, 2013).	Often unstable due to environmental variability and pesticide use (Morgan et al, 2016).	Locally stable in low input systems; unstable in intensively managed farms (Pal et al., 2024).
Climate Change Impact	Alters phenology, range, and interaction dynamics (Segoli et al, 2024).	Affects monsoon timing and pest–parasitoid synchrony (Prasad et al, 2025).	Highly sensitive due to reliance on monsoon-driven agriculture (Pal et al., 2024).
Research Status	Well-developed theoretical and empirical studies (Tylianakis & Binzer, 2024).	Moderate; increasing number of agroecosystem-based studies (Kumarswamy et al, 2024).	Limited long-term datasets; emerging research from regional instututions (Pal et al, 2024).

8.2 Comparative Percentage of Hymenopteran Parasitoids

Table 8.2: list of important hymenopterous parasitoids along with their hosts recorded from the vegetable ecosystems.

Parasitoid	Host insect	Crop(s)	Major activity	Highest incidence (%)
Aenasius arizonensis (=Aenasius bambawalei	*Phenacoccus solenopsis*	Tomato, Chilli, Okra, Brinjal	August-March	22.35
Diaeretiella rapae	*Myzus persicae, B. brassicae, L. erysimi*	Cabbage, Cauliflower	January-April	21.60
Pediobius foveolatus	*Epilachna vigintioctopunctata*	Cowpea, Brinjal	August-October	36.60
Campoletis chloridae	*Helicoverpa armigera*	Tomato, Pea	January-March	17.63
Apanteles paludicole	*Sphenerches caffer*	Bottle gourd	June-September	48.33
Trathala flavo orbitalis	*Leucinodes orbonalis*	Brinjal	August-March	17.25
Cotesia plutellae	*Plutella xylostella*	Cabbage, Cauliflower	February-April	22.35 25.75
Chelonus blackburni, Agathis sp.	*Earias vittella, E. insulana*	Okra	August-October	19.58
Microplitis tuberculifer	*Spodoptera litura*	Cauliflower	October-November	7.55
Cotesis glomerata	*Diaphania indica*	Cucumber	September-October	28.34
Neochrysocharis formosa	*Liriomyza trifolii*	Tomato, Marigold	December-March and January-March	37.50 48.30
Dinarmus basalis	*Callosobruchus chinensis, C. analis, C. maculatus*	Pea, French bean	July-October	33.33
Apanteles obliquae, Meteorus sp.	*Spilosoma obliqua*	Cowpea, French bean, Brinjal	March-April	22.86
Brachymeria lasus	*Diaphania indica*	Bitter gourd, Cucumber	August-October	19.20
Pristomerus euzopherae	*Euzophera perticella*	Brinjal	May- July	12.48

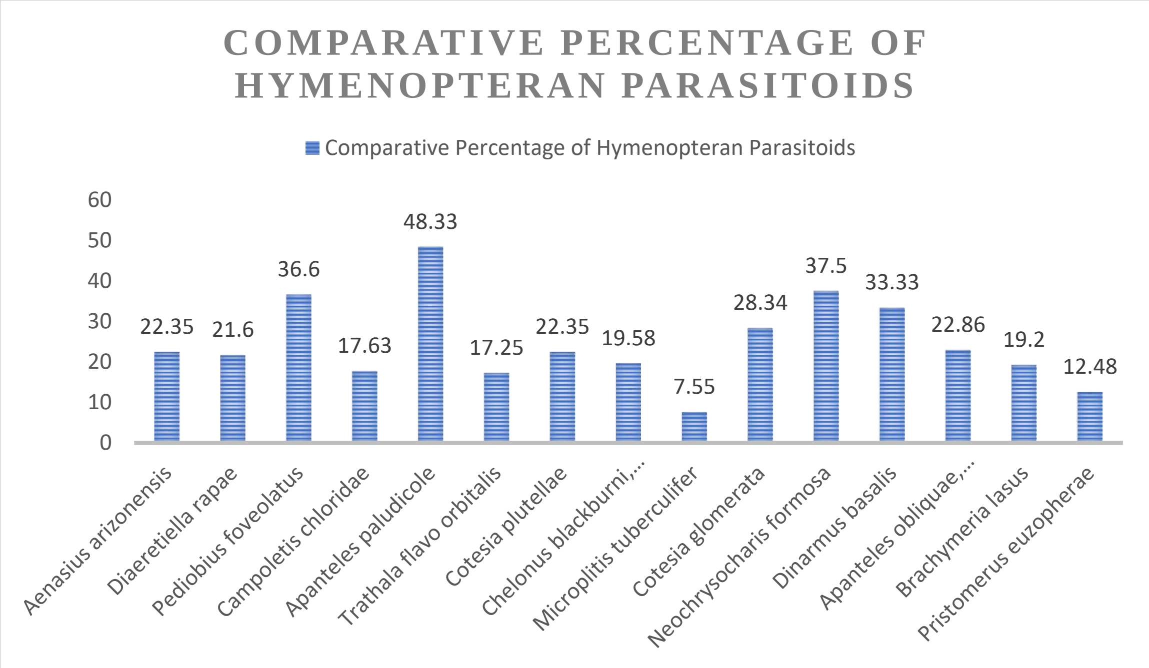

fig. 8. comparative percentage of hymenopteran parasitoids (Halder et al, 2018)

9. Hymenopteran Parasitoids Conservation and Habitats

Hymenopteran parasitoids is very important in sustainable pest management due to the beneficial role they play in natural enemies and pest population regulation.

9.1. Diversity of Habitat and Floral Resources

The flowering plants give parasitoids access to nectar and pollen, which are important for providing adults with food, long life span, reproduction (Han et al, 2024). The diversity of habitats and inclusion of flowering plants is highly important to ensure that parasitoids can thrive in the environment.

9.2. Conservation Biological Control Techniques

The minimization of pesticide use and utilization of bio-pesticides are key components together with timing of spraying to prevent interfering with parasitoid activities. Other techniques include crop rotation, intercropping, and creating refugia (Peñaflor et al., 2024).

9.3. Approaches to Ecological Engineering

This can be done through methods like the cultivation of nectariferous plants, (example, marigold, coriander) and the presence of non- crop plants. The effects of these methods have been proven to be positive in improving biological control results through tritrophic interactions (Roberts et al., 2019).

9.4. Climate Resistant Measures

Conservation efforts should take into account the climate resistance capabilities of the parasitoids. Habitat diversity and connectivity would ensure that there would be some sort of stability against environmental changes in order to sustain parasitoids. Conservation efforts aimed at habitat protection play a critical role in the continuation of these services provided by parasitoids (Hackett et al., 2024).

10. Future Research Perspectives

There is still considerable scope for new research even after many remarkable developments in parasitoid biology and biocontrol.

10.1. Molecular Taxonomy and Cryptic Diversity

The use of DNA barcodes and genomics can be very useful in terms of solving the problems related to identifying certain organisms. The morphology of these organisms cannot help researchers difference between various species of micro hymenopterans. Future work needs to be focused on the combination of molecular techniques with traditional taxonomy in order to solve the complex issue of cryptic species (Seehausen et al., 2020).

10.2. Exploration for Region-Specific Parasitoids

Mangroves of the Sundarbans, laterite areas, tea states in North Bengal would help in studying the parasitic fauna. There are many other regions that lack information regarding parasitoids and through surveys, many new species can be discovered.

10.3. Ecology and Behaviour of Parasitoids

Future research needs to focus on the ecological functions of parasitoids, especially with their host specificity, foraging behaviour, and multi trophic interactions.

10.4. Incorporation Into Contemporary IPM Strategies

Incorporating biological control methods, alongside precision agriculture, remote sensing, and decision support systems will enhance the incorporation process and success of parasitoid implementation.

11. Conclusion

The future of sustainable agriculture in West Bengal lies within the realm of hymenopteran parasitoids, which show great potential and have tremendous promise for being harnessed for ecological advantage and economic gain. It will be essential to conserve and integrate these hymenopterans into IPM practices for sustainable agriculture.

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