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An overview of biological control of economically important lepidopteron pests with parasitoids

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Abstract
The insect order Lepidoptera is one of the most important insect orders in terms of both species and agriculture point of view. Majority of these are the serious pest of most agricultural crops. Insects-pests are mostly management by using insecticides which are not only ineffective but also resulted in environmental pollution and diseases' outbreak. All these problems solution lies on the implementation of best IPM package. Biological control is one of the best options of Integrated Pest Management. Utilization of bio agent can easily be combined with other management techniques for having best IPM package. Parasitoids in this connection play a very important role in their management. These parasitoids attack the egg, larval or pupal stages of the host insects. In the present review the importance of parasitoids in controlling the different lepidopteron pests was discussed. The two major insect parasitoids orders hymenoptera with four families namely braconidae, ichneumonidae, chalcidae and trichogrammatidae and diptera with one family namely tachinidae in relation to biocontrol of selected lepidopteron pests have been studied. In addition the role of plant volatiles that play an important role in searching and locating their host and effect of temperature on the parasitoid performance has also been reviewed.

Keywords: Biological Control, Parasitoid, Braconidae, Lepidoptera, Herbivore Induced Volatiles.

1. Introduction
The insect order Lepidoptera is consider one of the most important order in relation to agricultural crops. This order includes moths and butterflies which are mostly destructive at larval stages. There are 126 families [1], 46 super families [2] with 180,000 species of insects [2] which account 10% of the total described species of living organisms [2]. To control these insect pests formars mostly rely on heavy pesticides uses in their fields as well as in storages. Over-reliance on chemicals has induced resistance in insect-pests thus leading to collapse of pest management programs. Additionally, a number of other problems are associated with extensive use of insecticides viz., human health concern, non-target effects, adverse effects on environmental health and many others. So an approach which combines all the eco-friendly compatible control methods should be utilized in order to manage the insect-pests i.e. integrated pest management. Biological control is "essentially a population phenomenon, resulting from the action of a natural enemy population interacting with a host population". Biological control is also referred as "the use of natural or modified organisms, genes, or gene products, plants or plants extracts to reduce the effects of unwanted organisms and to favor desirable organisms such as crops, microorganisms and useful insects" [3, 4].
Biological control programme have been observed against all pests species, however among other pests, insects are considered the most important and more than 1200 biocontrol programs have been reported [1]. Among the reported most of the insects belong to the insects order Homoptera, Coleoptera, Diptera and Lepidoptera.
There are three main different kinds of bio-control agents i.e. predators, parasitoids and entomopathogenic microorganisms. Among them, parasitoids are most important especially for lepidopteran pests. Parasitoids are special kind of natural enemy introduced against pest insects. Unlike true parasites, parasitoids kill their hosts and complete their development on a single host. Most parasitoids are Diptera or Hymenoptera, but a few are Coleoptera, Neuroptera, or Lepidoptera [5]. It has long been known that parasitoids can be used in insect-pest management in lieu of chemical insecticides. In the present review we are discussing the important insects parasitoids order with some important families in specifically related to lepidopteran pests.

Introduction to parasitoids

The term "parasitoid" describes insects that spend a significant portion of its life mostly in a parasitic relationship in attached or within a single host, usually kills its host and sometime consume the host [6]. Parasitoids comprise of 10% of all insects. There are four insect orders that are particularly prominent for this type of life history [7]. These are Hymenoptera, Diptera, Neuroptera and Coleoptera. Among these four insects order most of the parasitoids belongs to Hymenoptera and Diptera [7, 8]. Most parasitoids behaviors are so identical and specialized that they can attack only a particular host life stage i.e they are eggs parasitoids, larval parasitoids, pupal parasitoids, or adult's parasitoids, attacking eggs, larvae, pupae or adults stages respectively [5]. There are considerable variations in insect parasitoids parasitism. These may be idiobionts, whose hosts stop development, when they are parasitized. Idiobionts are either ectoparasitoids that kill their hosts or endoparasitoids that attack immobile host stages such as eggs or pupae. Koinobionts, allow the hosts to continue their development until the parasitoid's offspring matures. Most koinobionts are endoparasitoids of immature (larval) stages of insects, although a few are ectoparasitic [9]. In this review we are discussing the important hymenopteran and dipterous parasitoid families of the insect in relation to lepidopteran pests.

Hymenopteran parasitoids

Hymenopteran parasitoids constitute nearly 78% of the estimated number of reported parasitoid species and due to this great abundance; they have served as models of selection for nearly all modern research on insect parasitoids [10]. There are many parasitoids species belonging to different families in this order, however these four families namely Braconidae, Ichneumonidae, Chalcididae and Trichogrammatidae are very important in insect pest management [11].

Braconidae

This family is considered as one of the most important and largest in the order Hymenoptera, consisting of more than 15,000 valid species [12]. Family Braconidae along with the Ichneumonidae forms a distinctive superfamily among the assemblage of hymenopterans called as the parasitic wasps [13]. The adult braconids mostly oviposit in, on, or near other insects, with the immature stages completing their development at the host's expense. They are highly host specific, being so specific that as larvae only feed on a narrow host range. They are important in controlling many crop field insect pests like Lepidoptera and Diptera as shown in table 1. Braconids have been particularly heavily involved in the so-called classical biological control of insect pests and more recently in integrated pest management programmes, often with considerable success [14].

Chalcididae

The family Chalcididae consists of over 1500 species and 90 genera worldwide [15]. Chalcidids are mainly solitary, mainly endoparasitoids of Diptera and Lepidoptera as shown in table 1, though a few species attack neuroptera, coleoptera and hymenoptera. Most of them are idiobionts, depositing eggs into more or less fully grown hosts. These host stages may be as mature larvae (in the case of parasitoids of Diptera), or young pupae (in the case of Lepidoptera) [16].

Ichneumonidae

Family ichneumonidae is one of the most important parasitoid family which is further divided into 37 subfamilies with an estimated 60000 species in the world [17, 18]. Ichneumonids utilize a diverse group of insects as their hosts and play an essential role in the biological control of insects. The common host includes larvae and pupae of Lepidoptera, Coleoptera and Hymenoptera [19]. Some of the major ichnemonides parasitoids in specific relation to lepidopteran pests are shown in table 1.

Trichogrammatidae

This family consists of some tiny wasps with majority of insect species having adults size less than 1 mm in length. This family consists of 80 genera with approximately 840 species. Trichogrammatids parasitize the eggs of many different insects orders especially insect order lepidoptera and play an important role as biocontrol agent. The female after mating lay inside the host egg, the eggs when hatched feed on host eggs content. When fully mature, they pupate inside the host eggs and then adult emerge. The life cycle is completed in 8-12 days depending upon the environmental conditions [20]. The details of the most common hymenopter on parasitoids of the Trichogrammatidae which are associated with major lepidopteran pests are summarized in table 1.

Table 1: Reported Hymenopterous parasitoids in the family Braconidae, Ichneumonidae, Chalcididae and Trichogrammatidae associated with major Lepidopteran pests.

Name of the Insects species	Bio agent	Family	Reference(s)	Reported Regions
Lymantria dispar	*Glyptapanteles liparidis*	Braconidae	[21]	Europe
Phthorimaea operculella	*Bracon instabilis*	Braconidae	[22]	Africa
Pectinophora gossypiella Saunders	*Bracon brevicornis* Wesm	Braconidae	[23]	Africa
Plutella xylostella	*Apanteles litae var. operculellae Cotesia plutellae*	Braconidae	[24, 25]	Africa, Asia
Mythimna unipuncta	*Metorus gyrator* (Thunberg)	Braconidae	[22]	Asia
Manduca sexta	*Cotesia congregate*	Braconidae	[26]	North and Latin America
Antheraea mylitta Drury	*Apanteles angaleti* Muesebeck	Braconidae	[27]	Asia
Heliothis virescens/ Heliothis armigera/ Heliothis zea	*Microplitis croceipes/ Cotesia marginiventris/ Cardiochiles nigriceps*	Braconidae	[28]	America, Asia, Europe
Achroia grisella (F.)	*Apanteles galleriae* Wilk	Braconidae	[29]	Asia
Uraba lugens	*Cotesia urabae*	Braconidae	[30]	Australia
Phyllonorycter blancardella	*Pholetesor ornigis*	Braconidae	[30]	Australia
Pieris rapae/ Pieris brassicacea	*Apanteles glomeratus* L/ *Cotesia rubecula*	Braconidae	[31]	Asia, Europe

Rhyacionia bouliana	*Orgilus obscurator*	Braconidae	[32]	North America
Mamestra configurata	*Microplitis mediator*	Braconidae	[33]	North America
Ephestia cautella (Walker)	*Bracon hebetor* Say	Braconidae	[34]	Europe
Geina didactyla (L.)	*Apanteles pilicornis* Thoms	Braconidae	[35]	Europe
Tuta absoluta	Bracon F	Braconidae	[36]	Latin America
Ascia monuste orseis	*Cotesia glomerata*	Braconidae	[31]	South America
Diatraea saccharalis (Fabr.)	*Apanteles flavipes*	Braconidae	[37, 38]	America, Europe
Agrotis segetum/ Agrotis ipsilon	*Apanteles telengai Campoletis annulata*	Braconidae	[39]	Europe
Homoeosoma electellum	*Dolichogenidea homoeosomae*	Braconidae	[40]	America
Spodoptera frugiperda	*Chelonus insularis*	Braconidae	[41]	America
Ephestia kuehniella Zeller	*Bracon hebetor* Say	Braconidae	[42]	Africa
Plutella xylostella (L.)	*Diadegma semiclausum Diadegma mollipla Diadromus collaris Diadegma insulare Campoletis chlorideae Diadromus subtilicornis*	Ichneumonidae	[43, 44, 45]	Europe, Asia, Africa
Heliothis armigera Hb	*Hyposoter didymator Campoletis chlorideae Campoletis chlorideae Campoletis sonorensis*	Ichneumonidae	[46, 47, 48, 49]	Asia, America
Spodoptera litura	*Diadegma argenteopilosa*	Ichneumonidae	[50]	Asia
Acrolepiopsis assectella	*Diadromus pulchellus*	Ichneumonidae	[51]	Europe
Cydia pomonella	*Mastrus ridibundus Diadegema semiclausum*	Ichneumonidae	[52]	America
Ostrinia nubilalis Hbn	*Eriborus terebrans*	Ichneumonidae	[53]	Europe
Agrotis segetum	*Campoletis annulata Pimpla turionellae Meteorus rubens*	Ichneumonidae	[54]	Europe
Petrophila confusalis	*Tanychela pilosa*	Ichneumonidae	[55]	America
Lymantria dispar	*Brachymeria intermedia*	Chacididae	[56]	Asia
Tuta absoluta	*Hockeria unicolor Spilochalcis* sp	Chacididae	[57, 58]	South America, Europe
Malacosoma Neustria	*Brachymeria secundaria*	Chacididae	[59]	Asia
Thyrinteina leucocerae	Brachymeria Pandora	Chacididae	[57, 58]	South America
Ostrinia nubilalis	*Trichogramma nubilale Trichogramma brassicae*	Trichogrammatidae	[60]	America, Europe
Tuta absoluta	*Trichogramma pretiosum*	Trichogrammatidae	[61]	Europe
Spodoptera frugiperda	*Trichogramma pretiosum*	Trichogrammatidae	[62]	South America
Helicoverpa zea	*Trichogramma pretiosum Trichogramma australicum*	Trichogrammatidae	[62, 63, 64]	South America, Australia
Pectinophora gossypiella	*Trichogrammatoidea bactrae*	Trichogrammatidae	[65]	America
Acrobasis vaccinia	*Trichogramma pretiosum*	Trichogrammatidae	[66]	America
Chilo infuscatellus	*Trichogramma chilonis*	Trichogrammatidae	[67, 68, 69]	Asia, Africa
Emmalocera depresella	*Trichogramma chilonis*	Trichogrammatidae	[67, 68, 69]	Asia, Africa
Chilo Scirphophagus	*Trichogramma chilonis*	Trichogrammatidae	[69]	Africa
Cydia pomonella	*Trichogramma minutum Trichogramma platneri*	Trichogrammatidae	[70, 71]	America, Asia

Dipterous Parasitoids

The insect order diptera includes several families with an estimated 16,000 species of parasitoids, or approximately 20% of the total number of species with this life-style. Among these parasitoids families, Tachinidae is the largest and most important family consisting of about 10,000 parasitoids of the major agricultural pests [7]. All tachinid flies are larval parasitoids of insects. Most tachinid flies are larger than a house fly, but they range in size from 2–20mm. Mostly they are endo parasite and majority of are ovoviviparous, depositing eggs that contain fully developed first instars. The primary host includes lepidopterans pests but some species attack coleopterons insects [72]. Some of the most common dipteran parasitoids of the the family tachinidae are described in table 2 with specifically in relation to lepidopteran pests.

Table 2: Reported dipteran parasitoids in the family Tachinidae associated with major Lepidopteran pests.

Name of the Insects species	Bio agent	Family	Reference	Reported Regions
Agrotis segetum	*Periscepsia carbonaria*	Tachinidae	[73, 74, 75]	Asia
Apamea Illyria	*Linnaemya haemorrhoidalis*	Tachinidae	[76]	Asia
Cosmorhoe ocellata	*Trafoia monticola*	Tachinidae	[77]	Asia
Helicoverpa gelotopoeon	*Archytas sp*	Tachinidae	[78]	Europe
Galleria mellonella	*Galleria mellonella*	Tachinidae	[79]	Europe
Ostrinia nubilalis	*Lydella thompsoni*	Tachinidae	[80]	Europe
Streblote panda	*Drino maroccana*	Tachinidae	[81]	Europe
Neoleucinodes elegantalis	*Lixophaga* Townsend	Tachinidae	[82]	South America
Helicoverpa armigera	*Senometopia illota Archytas marmoratus Linnaemya longirostris*	Tachinidae	[83, 84]	Asia
Mythimna separate	*Drino inconspicuoides*	Tachinidae	[85]	Asia
Actias luna	*Compsilura concinnata*	Tachinidae	[86]	America
Notolophus antiqua Linn	*Blepharipa zebina*	Tachinidae	[85]	Asia
Lymantria dispar	*Ceranthia samarensis*	Tachinidae	[87]	North America

Parasitoid Host Attraction to lepidopteran pests

3.1 Parasitoids attraction by herbivore induced volatile

The volatile chemicals-whether derived from organisms associated with the host, the host itself, the host's food, or a blend of these factors-are mainely responsible for attracting the parasitoid to a host habitat. Blends of volatile chemicals from the plants are released into the air after insect herbivores attack. Many studies have shown this phenomenon for numerous plant species [88]. The plant uses these chemical for several purposes including direct protection against insect herbivores [89], attraction of natural enemies of herbivore within plant signaling [90]. The attraction of natural enemies of herbivore has been the main concern of most researchers in this field, and many species of predators and parasitoids including birds, insects, nematodes and mites associated with herbivore damage have been confirmed to be attracted by these plant volatiles [88, 91, 92]. A similar study was conducted by Turlings *et al*., [93] in the host seraching behavior of larval parasitoids of lepidopterans and reported that the attraction of parasitoids toward odorous cues emitted by damage plants. Similarly in young corn seedlings, a few hour after the caterpillar damage, several highly odorous terpenoid are released to attract the natural enemies in response to larval damage. This response is systemic, as the same terpenoids are also released from undamaged leaves of injured plants [93].

The insect damages to plants resulted in induced plant volatiles which are called herbivore induced plant volatiles which attract the natural enemies of the pest species and in this way protect the crop [94]. HIPVs are plant secondary metabolites that enhances many multi-trophic connections in both above- and below-ground plant–insect communities [94]. Over the past few years these HIPVs have received greater attention for their role in attracting natural enemies of major lepidopteran pests. Some of the HIPVS that attract the natural enemies of the pests especially lepidopteran is presented in table 3.

Table 3: Some of the important plant volatiles that are involved in parasitoid attraction of lepidopteran pests

Name of the Insects species	Bio agent	Family	Source	Chemical	Reference
Lymantria dispar	*Glyptapanteles liparidis*	Braconidae	Damage host plant leaves	nitrogen-containing compounds, the nitrile benzyl cyanide and 2- and 3-methylbutyraldoxime	[95]
Heliothis zea	*Cardiochiles nigriceps*	Braconidae	Damage host plant leaves i.e. Tobacco and Zea mays	(*Z*)-3-hexen-1-ol; 2, (*Z*)-3-hexenyl acetate; 3, (*E*)-b-ocimene; 4, linalool; 5, (*E*)-4,8-dimethyl-1,3,7-nonatriene; 6, indole; 7, b-caryophyllene; 8, a-*trans* bergamotene; 9, (*E*)-b-farnesene; 10, (*E*,*E*)-4,8,12-trimethyl-1,3,7,11-tridecatetraene.	[96]
Spodoptera exigua and *Spodoptera frugiperda* on corn	*Cotesia marginiventris*	Braconidae	Corn seedling and leaf damage by catterpilars	lipoxygenase-derived volatiles((Z)- 3-hexenal, (E)-2-hexenal, (Z)-3-hexenol, (E)-2-hexenol, and (Z)-3-hexenyl acetate) Terpenoids([linalool, (3E)-4,8-dimethyl-1,3,7-nonatriene, a-trans-bergamotene, (E)-P-farnesene, (E)-nerolidol, and (3E,7E)-4,8,12-trimethyl- 1,3,7,11-tridecatetraene] and Indole	[97]
Pieris spp.	*Cotesia glomerata*	Braconidae	Cabbage and Related sub-species		[98,99]
Heliothis zea/ *Helicoverpa zea*	*Microplitis croceipes*	Braconidae	Cotton, cow pea and maiz	13 methyl hentriacontane	[100]
Rhyaciona buoliana	*Pimpla ruficolli*	Ichneumonidae	Larvae feed on pine shoot	Pine Oil	[101]

3.2 Role of shape and texture of the plant in attracting lepidopteran parasitoids

As discussed earlier that plant volatiles play an important role in selection of host by parasitoids, but there are some other factors like shape and texture of the host also play important role in addition to these HIPVs. Odour and chemicals have been demonstrated to be of major importance in host. The shape and texture of the host influence acceptance by parasitoids. *Pimpla instigator* (Ichneomonidae) endoparaitoid of the P*ieris brassicae* and *Lymentria dispar* are primerally attracted to the odor while the cylindrical shape of the host plant influences the degree of acceptance of a host [102]. Small hole with round or concave shape plays an important role for attracting the *Macrocentrus ancylivorus*, a parasitoid of the potato tuber moth, *Tuta absoluta* towards potaoto plant [103]. Weseloh [104] reported that odour and hairiness were important for the acceptance and attraction of the *Apanteles melanoscelus,* one of the parasitoid of the gypsy moth, *Lymantria dispar*. It can be concluded from many studies that the shape and texture also play an important role in addition to plant volatiles in the acceptance of a host [103, 105, 106].

Impact of temperature on the behaviour and development of the lepidopterans pests

In order to obtain a stable host parasitoid system, the developmental duration of the parasitiod must be 0.5 to 1.5 times the duration of its host development and also the duration of immature stages of both parasitiods and host must be longer than the adult life span [107]. A slight change in this ration will result in disequilibrium of the interaction. In a study, braconid wasp (C*otesia melitaearum*) pupal cocon develops slowly in a cold climatic condition, whereas its host *Melitaea cinxia* (Lepidoptera; Nymphalidae) larvae searched for open sunny microclimate resulting in increased body temperature and rapid development. Then later on in the sunny spring when the parasitoids emege from the cocoon, so most of the host larvae were pupated and were no more available for parasitization. So synchnozation between parasitoids and its host play important in natural enemy interaction [108]. Exposure to traumatic temperatures encourages lethal and sublethal damages to parasitoids. It generally decreases mobility, fecundity, longevity, learning capacities, production of paired sex ratio and the ability to orient themselves toward attractive odors [109].

Future Perspectives and conclusions

Biological control is a promising solution for both pest problems in agriculture and environmental protection of natural ecosystems worldwide. With the introduction of new technologies and better information sharing and networking among the world's biological control community and availability of easily accessible databases containing detail studies on natural enemies (with appropriate evaluation) will help to increase the rate of identification of new and efficient control agents. The present review suggested that the insect order lepidoptera is one of the most important order with many pests' species of agriculture produce. In nature different bioagent are associated with lepidopteran pests in which only parasitoids are considerd to play a vital role in controlling their population. Many factors are associated in attracting and searching of the host, the most important of which appears to be plant volatiles (HIPVs). These plant volatiles not only attract the parasitoids but also act as a repellent and protect the crop from insect herbivore. Further research is needed to isolate these environment friendly plant volatiles and to test these HIPVs against many lepidopteran pests that aid many parasitoid species in locating and searching of their host.

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