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HYMENOPTERAN PARASITOIDS AS A BIOLOGICAL CONTROL AGENT OF POTATO TUBER MOTH *PHTHORIMAEA OPERCULELLA* (LEPIDOPTERA: GELECHIIDAE): A REVIEW

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ABSTRACT: Potato tuber moth (PTM), *Phthorimaea operculella* Zeller (Lepidoptera: Gelechiidae) is the most destructive and cosmopolitan oligophagous pest of potato and many Solanaceous crops. Larvae damages potato leaves and tuber in both field and storage and causing significant yield losses. Chemical management of PTM through the use of pesticides is challenging, as the extensive application of these chemicals to control the pest leads to numerous health problems, destruction of beneficial organisms, and the development of insecticide resistance in pest populations. A safe and sustainable approach to pest control is to use parasitoid wasps as biological control agents. In this review, sixty-five species of parasitoid wasps of PTM under six families (Braconidae, Chalcididae, Encyrtidae, Eulophidae, Ichneumonidae and Trichogrammatidae) have been reported. *Copidosoma koehleri* (Hymenoptera: Encyrtidae), *Apanteles subandinus* (Hymenoptera: Braconidae), *Orgilus lepidusa* (Hymenoptera: Braconidae) have been successfully introduced to control PTM worldwide. In warm environmental conditions, *Trichogramma principium* (Hymenoptera: Trichogrammatidae) is a better candidate for mass rearing and release as a biological control agent against PTM. Under favorable environmental conditions, successful parasitoid establishment is achievable through intercropping, combined releases of parasitoids from diverse families and sterile PTM, selective pesticide application, and improved mass rearing technologies. This review provides insights that can assist policymakers in making informed decisions for more effective pest management programs.

Key words*:* Biological control, parasitoid wasps, *Phthorimaea operculella,* hymenoptera, potato tuber moth.

INTRODUCTION

Potato, *Solanum tuberosum* L. is a staple food crop in many countries of the world and ranks fourth among the world's most important food crops, after wheat, rice, and maize (Meabed *et al.* 2011). Due to its nutritional value and

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quantity of production, it is a key food source in global diet (Burgos *et al.* 2020). Production of potato is affected by a large number of insect pests such as aphids, leafhoppers, and lepidopterous pests, as well as various diseases that occur under field conditions (Mandour *et al.* 2012). Among these pests, the potato tuber moth (PTM), *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae) is regarded as one of the most destructive, with a global distribution and an oligophagous feeding behavior that targets potatoes as well as various other Solanaceous crops (Mandour *et al.* 2012, Zheng *et al.* 2020). This moth is distributed in almost all tropical and subtropical potato-producing countries (more than 90 countries) in Asia, Africa and Central and South America (Chandel *et al.* 2020).

The damage was caused by the larval feeding on potato leaves, stems, and petioles in the field and causing significant yield losses (Frank *et al.* 2008, Symington 2003) and in warm climates losses can reach 100% (Tsedaley 2015). The control of PTM is very difficult and farmers have been dependent extensively on the use of insecticides and a wide variety of cultural practices over the years (Rondon 2010). Due to the protected tunneling behavior of PTM larvae within potato tubers and foliage, chemical management becomes particularly challenging (Tsedaley 2015). This pest has developed resistance to many commonly used insecticides as a result of extensive and repetitive chemical applications. Such resistance exacerbates pest management challenges, alongside human health risks from pesticide exposure and harm to beneficial organisms (Meabed *et al.* 2011, Tsedaley 2015). To mitigate these challenges, Integrated Pest Management (IPM) programs have been developed to reduce reliance on chemical pesticides. Biological control, a cornerstone of IPM, offers a sustainable alternative for managing *PTM* while minimizing environmental and health risks (Meabed *et al.* 2011).

An environmentally friendly and sustainable approach is biological control where natural enemies (predators, parasitoids, or pathogens) are used to control pest population. In classical biological control, invasive pests are managed through introduction of exotic natural enemies. Augmentative biological control involves the inoculative release of exotic natural enemies to suppress pest population. In conservation biological control, it ensures a sound environment for natural enemies by avoiding insecticide use or optimizing the pesticide application (Lacey and Kroschel 2009).

Parasitoid wasps are a group of insects which use other insects as their host and kill the host. That is why parasitoid wasps are well-known biological control agents for arthropod pests in agricultural and forest ecosystems (Zhi-zhi *et al.* 2019). Rondon (2010) reviewed over 60 Hymenopterous parasitoids of PTM from families including Braconidae, Encyrtidae, Eulophidae, Ichneumonidae, Mymaridae, Perilampidae, Pteromalidae, Scelionidae, and Trichogrammatidae. A subsequent review by Rondon and Gao (2018) identified 36 parasitoids known to control PTM. Despite these efforts, there remains a lack of a comprehensive review on parasitoid wasps of PTM. Therefore, this review aims to compile information on these parasitoid wasps, offering an overview of their species diversity to enhance biological control of PTM.

Overview of Parasitoids: Parasitoids are a group of insects whose larvae feed and develop within or on the bodies of other arthropods and eventually kills the host (Shaw and Huddleston 1991, Gauld 1988). Usually, the host are immature stages of other insects and the adult stage of host are free living (Shaw and Huddleston 1991). Parasitoids occur in seven holometabolous orders of insects including Hymenoptera (Kim *et al.* 2015). About 78% of the reported parasitoids are hymenopteran parasitoid and due to their great abundance, they have served as models of selection of modern research in insect parasitoid (Salim *et al.* 2016).

Hymenopteran Parasitoid Families: In Hymenoptera, there are many parasitoid species belonging to different families. This review described six parasitoid families such as Braconidae, Chalcididae, Encyrtidae, Eulophidae, Ichneumonidae and Trichogrammatidae under the order Hymenoptera.

Braconidae: Among hymenopteran parasitoid, Braconids are large and economically important family (Beardsley 1961). All parasitoids of braconid live on other insects, develop as larvae on tissues of the host and finally killed the host (Shaw and Huddleston 1991). They are highly effective larval parasitoids of various species within the orders Coleoptera, Diptera, and Lepidoptera, many of which are significant agricultural and forest pests. Most braconid parasitoids exhibit a high degree of host specialization, targeting specific host species (Shaw and Huddleston 1991).

Chalchididae: The family Chalcididae is a moderate sized family within the superfamily Chalcidoidea. Chalcidids are mostly parasitoids, including a minority of hyperparasitoids on a wide range of holometabolous insect hosts such as Lepidoptera, Diptera, Hymenoptera, Coleoptera, Neuroptera and Strepsiptera as the chalcidid adults always emerge from the pupae, whenever the oviposition occurs **(**Lotfalizadeh *et al.* 2012).

Eulophidae: Eulophidae is one of the largest and most diverse families of parasitic wasps. Most eulophids are generally parasitoids of holometabolous insects. They may be ectoparasitoids or endoparasitoids. Several species of Eulophidae are important in biocontrol programs throughout the world (Hesami 2010).

Ichneumonidae: It is a large family of parasitic wasps. Ichneumonids are parasitoids of Lepidoptera, Hymenoptera, Diptera, Coleoptera and rarely spiders

Table 1. List of reported parasitoid wasps of PTM

Scientific Name	Country	Reference
Family: Braconidae		
Agathis unicolorata Shenefelt	South America	Chandel *et al.* 2020
Agathis gibbosa	USA	Ọdẹbiyi and Oatman 1977
Apanteles litae	-	Salama *et al.* 1996
Apanteles dignus Muesebeck	-	Flanders and Oatman 1987
Apanteles subandinus Blanchard	South Africa, South America, Australia, Zimbabwe, India	Chandel *et al.* 2020, Lacey and Kroschel 2009, Rondon 2010, Rondon, 2020
Apanteles scutellaris	India, USA	Flanders and Oatman 1987
Bracon gelechiae Cameron	India, USA	Chandel *et al.* 2020, Frank *et al.* 2008, Zheng *et al.* 2020
Bracon hebetor Say	India, USA	Chandel *et al.* 2020
Bracon instabilis	-	Salama *et al.* 1996
Bracon nigricans L.	-	Rondon and Gao 2018
Bracon properhebetor L.	-	Rondon and Gao 2018
Chelonus blackburni Cameron	India	Chandel *et al.* 2020, Keasar and Sadeh 2007
Chelonus contractus	France	Rondon and Gao 2018
Chelonus curvimaculatus (synonym: *Microchelonus curvimaculatus*)	South Africa	Flanders and Oatman 1987
Chelonus kellieae	USA	Flanders and Oatman 1987
Chelonus phthorimaea	USA	Flanders and Oatman 1987
Habrobracon gelechiae	US Pacific Northwest	Rondon 2010
Microgaster phthorimaea	USA	Flanders and Oatman 1987
Orgilus californicus	USA	Flanders and Oatman 1987
Orgilus parcus Turner	South Africa	Chandel *et al.* 2020
Orgilus jennieae Marsh	India, USA	Chandel *et al.* 2020
Orgilus lepidus Muesebeck	Australia	Chandel *et al.* 2020, Lacey and Kroschel 2009, Rondon 2010, Saour 2004
Parahormius pallidipes	USA	Flanders and Oatman 1987
Two unidentified	-	Coll *et al.* 2000
Zagrammosoma flavolineatum	USA	Flanders and Oatman 1987
Family: Chalcididae		
Brachymeria lasus Walker	-	Zheng *et al.* 2020
Brachymeria marginate	-	Chandel *et al.* 2020
Family: Encyrtidae		
Copidosoma desantisi Annecke and Mynhardt	Australia	Rondon, 2010
Copidosoma koehleri Blanchard	South Africa, South America, Australia, Zimbabwe, Israel, Italy	Chandel *et al.* 2020, Frank *et al.* 2008, Rondon 2020, Zheng *et al.* 2020
Copidosoma uruguayyensis Tachikawa	South America, South Africa	Rondon 2020
Family: Eulophidae		
Elasmus funereus	Australia	Franzmann 1980
Euderus sp.	USA	Flanders and Oatman 1987
Ostrinia nubilalis Hübner	Italy	Pucci *et al.* 2003
Phyllonorycter cerasicolella Herrich-Schäffer	Italy	Pucci *et al.* 2003
Pnigalio pectinicornis L.	Italy	Pucci *et al.* 2003
Sympiesis sp.	-	Zheng *et al.* 2020
Sympiesis stigmatipennis	USA	Flanders and Oatman 1987
Sympiesis viridula Thomson	Italy	Pucci *et al.* 2003
Family: Ichneumonidae		

Scientific Name	**Country**	**Reference**
Campoletis chlorideae Uchida	India	Chandel *et al.* 2020, Zheng *et al.* 2020
Campoplex haywardi Blanch.	USA	Chandel *et al.* 2020, Flanders and Oatman 1987
Campoplex phthorimaeae	USA	Flanders and Oatman 1987
Cremastus hapaliae Cushman	India	Chandel *et al.* 2020
Diadegma fenestrale L.	Korea	Rondon and Gao 2018
Diadegma malliplum	India, South Africa	Chandel *et al.* 2020
Diadegma compressum	USA	Flanders and Oatman 1987
Diadegma pulchripes Kokujev	Israel	Coll *et al.* 2000, Pucci *et al.* 2003, Zheng *et al.* 2020
Diadegma surendrai Gupta	-	Chandel *et al.* 2020
Diadegma stellenboschense Cameron	South Africa	Chandel *et al.* 2020
Diadegma turcator Aubert	-	Chandel *et al.* 2020
Eriborus trochanteratus Morley	India	Chandel *et al.* 2020
Nepiera fuscifemora	USA	Flanders and Oatman 1987
Nythobia sp.	USA, India	Flanders and Oatman 1987
Pristomerus vulnator	India	Chandel *et al.* 2020
Pristomerus spinator	USA	Flanders and Oatman 1987
Temelucha picta	-	Watmough *et al.*1973
Temelucha decorate Gravenhorst	-	Coll *et al.* 2000, Zheng *et al.* 2020
Temelucha minuta	Australia	Franzmann 1980
Temelucha sp.	-	Chandel *et al.* 2020, Zheng *et al.* 2020
Family: Trichogrammatidae		
Trichogramma brasiliensis	Australia	Saour 2004
Trichogramma cacoeciae	-	Saour 2004
Trichogramma chilonis	India	Meabed *et al.* 2011
Trichogramma evanescens West	Egypt	Meabed *et al.* 2011, Meabed *et al.* 2012
Trichogramma pretiosum	-	Saour 2004
Trichogramma principium	-	Saour 2004, Saour 2009

and other arthropod groups (Barahoei *et al.* 2012). All of the Ichneumonidae are parasites as larvae and free-living as adults. Most species parasitize only insect larvae or pupae. Although a few ichneumonids lay their eggs inside insect eggs, it is the developing larva or pupa that emerges from the egg and is ultimately killed by the parasitoid. In the Ichneumonidae, oviposition into the egg is only a convenient way of getting into the larva or pupa and there are no true egg parasites in the family (Townes 1958).

Reported Hymenopterous parasitoids of PTM: A total of 65 parasitoid species, including two unidentified species, have been reported as parasitoid wasps of the PTM under six families. Of those, 26 species belong to the Braconidae (Genus *Agathis, Apanteles, Bracon, Chelonus, Habrobracon, Microgaster, Orgilus, Parahormius, Zagrammosoma*); 2 species to the Chalcididae (Genus: *Brachimeria*); 3 species to the Encyrtidae (Genus: *Copidosoma*); 20 species to the Ichneumonidae (Genus: *Campoplex, Campoletis, Crematus, Diadegma, Eriborus, Nepiera, Nythobia, Pristomerus, Temelucha*); 8 species to the

Eulophidae (Genus: *Elasmus, Euderus, Ostrinia, Phyllonorycter, Pnigalio, Sympiesis*); and 6 species to the Trichogrammatidae (genus: *Trichogramma*) (Table 1).

Major Parasitoids for PTM Management: Widely used parasitoids to control PTM are *Apanteles, Copidosoma, Orgilus, Diadegma, and Trichogramma* (Horne 1990, Mandour *et al.* 2008, Pucci *et al.* 2003). Indigenous parasitoids are important for reducing the PTM (Watmough *et al.* 1967). Many countries successfully introduced parasitoids in the field to control PTM.

Copidosoma koehleri: Copidosoma koehleri is an egg-larval polyembryonic parasitoid that originated in South America and was successfully introduced in Australia, South Africa (Keasar and Steinberg 2008, Pucci *et al.* 2003). In Zimbabwe, *C. koehleri* is used to control PTM, and no need for pesticide use (Pucci *et al.* 2003). Keasar and Steinberg (2008) have demonstrated that augmentative release of *C. koehleri* in Israel is not successful and the parasitism rate was 4-5%. This can also be interpreted to be due to the inability of introduced parasitoids to find the host and the unfavorable abiotic condition. The relative humidity is one of the major factors that affect the relative abundance of *C. koehleri*. Kfir (1981) has indicated *C. koehleri* is susceptible to low humidity and prefers high humidity (70% relative humidity) which increases longevity and fertility. In South Africa, when *C. koehleri* was introduced in combination with *Apanteles subandinus*, maximum parasitism (65-90%) was recorded which depends on host density or insecticide application (Kfir 1981). In Italy, the introduction of *C. koehleri* was not successful and parasitism rate was maximum 3% due to low relative humidity which was modest all over the year and less than 20%. In contrast, indigenous parasitoids (*Diadegma pulchripes, Pnigalio pectinicornis*, and *Sympiesis viridula*) achieved a parasitism rate of 23%, likely due to their better adaptation to the local climatic conditions and ecological niches (Pucci *et al.* 2003). Introduction of *C. koehleri* in combination with a braconid parasitoid (*Apanteles* sp.) or the application of a bioinsecticide may enhance parasitism rates. This synergistic effect can be attributed to complementary interactions between these control agents (Canedo *et al.* 2016). While *C. koehleri* primarily targets the egg-larval stages of the host, *Apanteles* sp. is a larval parasitoid, which broadens the range of host developmental stages being parasitized, thereby increasing overall pest suppression (Cardona and Oatman 1975, Keasar and Sadeh 2007).

Planting non-host food plants around potato fields which increases the longevity and parasitism rate of *C. koehleri* (Baggen and Gurr 1998). Non-host plants provide additional resources such as nectar and pollen, which serve as supplemental food sources for adult parasitoids. These resources enhance the parasitoids' survival, reproductive capacity, and effectiveness in controlling pests (Baggen and Gurr 1998).

Trichogramma sp.: In many potato-producing areas, temperatures frequently exceed 35°C. Under such warm environmental conditions, *Trichogramma principium* is a better candidate for mass rearing and release as a biological control agent against PTM, as it is more effective at high temperatures (36°C) (Saour 2004). In contrast, *T. cacoeciae* and *T. evanescens* fail to complete their development at this temperature, making them less suitable for use in these conditions (Saour 2004).

Integration of bioinsecticides (such as Neemex, Virotecto, Agerin, Dipel 2x and Spinosad) with *T. evanescens* enhances the control of PTM in storage (Mandour *et al.* 2012). Saour (2009) has pointed out that release of *T.principium* parasitoid eggs in combination with sterile PTM significantly reduces the PTM in storage compared to the single release of *T. principium* eggs alone.

Apenteles sp.: Apenteles subandinus is an effective parasitoid against PTM and was introduced in many countries in combination with *C. koehleri* and *O. lepidus*. In Zambia and Cyprus, after the establishment of the introduced parasitoid, PTM became rare. More than 70% parasitism rate is found in Australia (Canedo *et al.* 2016).

Factors affecting the parasitism rate: The effectiveness of parasitoids in controlling PTM is influenced by various environmental and ecological factors, including temperature, humidity, availability of non-host food plants, and intercropping practices.

Temperature: Temperature significantly affects the emergence of parasitoids from parasitized eggs. The optimum temperature for any species in trichogrammatidae to express high reproductive performance ranges from 24-30° C (Saour 2004).

Humidity: Kfir (1981) has pointed *A. subandinus* is more fertile and lives longer at low humidity and *C. koehleri* prefers high humidity. Low humidity with high temperature reduces *C. koehleri* survival rate (Keasar and Steinberg 2008).

Non-host food plant: Baggen and Gutt (1998) have indicated non-host food plants around potato fields increase the longevity and parasitism rate of *C. koehleri*.

Intercropping: Zheng (2020) has revealed the host/non-host intercropping patterns in potato fields enhancing the density of parasitoid and parasitism rate. Where environmental conditions are favorable, successful establishment of parasitoid is possible by intercropping, releasing parasitoid with a combination of different parasitoid family and sterile PTM, using selective pesticide, and improving mass rearing technologies.

CONCLUSION

To overcome or minimize the use of pesticides, knowledge of biological control using parasitoids will help in pest management which is crucial for sustainable agriculture. To translate new knowledge in parasitoid biology into effective biological control technologies, applied research is becoming increasingly important.

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