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Parasitoid wasps as biological control agents: A review

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Abstract
Biological control is an important weapon in favour of sustainability in agricultural systems. Parasitoidea is a monophyletic hymenopteran lineage that involves species with parasitoid lifestyle, e.g. the known families Braconidae and Ichneumonidae. The use of parasitoids as natural enemies for suppressing harmful insects is an ecofriendly action aiming the reduction of chemical spraying in crop protection. Parasitoid guilds, such as egg, larvae and pupal parasitoids have great potential of introduction in biological control programs. This review discusses the current bibliography about the use of parasitoid wasps as natural enemies, different guilds and ecological interactions inside an Integrated Pest Management (IPM) context.

Keywords: Braconidae, crop protection, guild, natural enemy, pest control

1. Introduction

Biological control, a pillar of Integrated Pest Management (IPM), is a highly successful method for pest control [1, 2]. Conservative methods or flooding releases of natural enemies tend to reduce the damage caused by pests to crops and prevent their populational growing in an environmentally safe way. Agronomists and farmers may consider such strategies due to possible replacement, partial or integral, of agrochemicals by an equivalent effective and costless agent [3]. Successful applications of biological control have been widely reported, but the introduction of such agents into the market still face barriers [3]. In Brazil, the use of biological control has increased 20 percent annually, while the rest of the world was 10-15 percent in the last decade [3, 4]. The continuous progress of Brazilian biological control is a combination of massive academic research coupled to industrial interest, which is confirmed by the commercial availability of biological control agents (Table 1). Another important example is Australia, where in the first half of the last decade had more than 36 invertebrate species available in the market for biological control in crops [5]. Nowadays, approximately 500 companies in the world trade dozens of arthropods as biological control agents, especially Europeans, with 75 percent of all biological control market share [3, 5, 6, 7]. For introducing a biological control agent into an IPM program, the ecological context in which the new species shall face have to be understood for a correct implementation. Populations do not occur in isolation, but in an interdependent system with environmental factors that directly affects their dynamics [8, 9]. Previous studies on multitrophic relationships are of paramount importance and it should be considered that a tritrophic relationship (plant x pest x natural enemies) is intertwined with several other multitrophic interactions [10]. Furthermore, the uncountable guilds present in an ecosystem influence directly on the strategy of delivery for a successful pest control [11]. Thus, this work addresses the current research and general characteristics of parasitoid wasps reported as potential or stablished biological control agents.

2. Parasitoid Wasps

Parasitoids are insects whose life pass partially through a host body and usually feed on only one host to complete their cycle. Although Hymenoptera and Diptera are the main orders with known parasitoid species, Lepidoptera, Coleoptera and Neuroptera also have parasitoid species described [11]. Parasitoidea is a hymenopteran monophyletic group inside the suborder Apocrita and is characterized by the parasitoid lifestyle [12]. This group has developed several strategies of host regulation. Among those strategies, briefly we may highlight the injection of venom toxins, teratocytes release, poliDNA virus and virus-like molecules with physiological regulatory function [13, 14, 15, 16].

A main host regulation function is the humoral and cellular immune disruption, especially for protecting the embryos [17]. Parasitoid guilds can be sorted according to offspring number per host, how they kill their host and the stage that their host is parasitized (Fig. 1). Several different parasitoid guilds have been recorded and described according to their lifestyle and behaviour [11, 18, 19]. All these diverse guilds have an unexplored potential in agriculture, especially because thousands of parasitoid species remain undescribed [20].

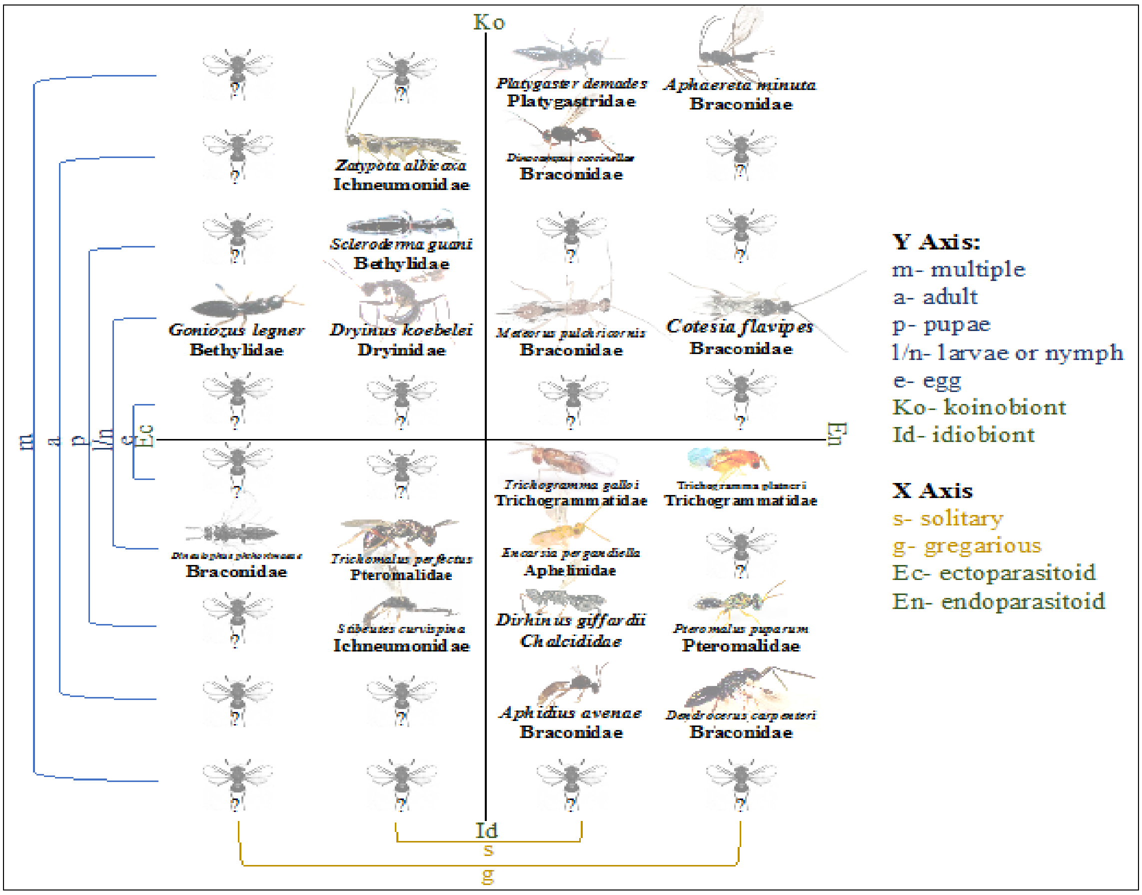

Fig 1: Examples of Parasitoidea species from known guilds, according to their lifestyle. They are sorted according the stage in which parasitization occurs (egg, larvae/nymph, pupae, adult or multiple), mode of parasitization (koinobiont, idiobiont, ectoparasitoid and endoparasitoid) and the number of parasitoids per host (solitary and gregarious). Groups with unknown species are filled with a question mark (?).

3. Egg parasitoids

The greatest advantage of using egg parasitoids is that the hosts are killed before causing any damage to the plants. All the known egg parasitoids are endoparasitoids idiobionts, but there are reports of egg-larvae parasitoids, such as *Chelonus inanitus* (Hymenoptera: Braconidae), considered as multiple stage parasitoids. In Brazil, the application of the egg parasitoid *Trichogramma galloi* (Hymenoptera: Trichogrammatidae) for controlling the sugarcane stem borer, in 5 years has increased from 6 to 22 percent of the total sugar cane area, totalizing two million ha [21, 4]. Due to its efficacy, in Brazil *T. galoi* is highly commercially explored, with seven registered products (Table 1).

For the implementation of a successful biological control program using egg parasitoids, it is necessary to consider their preference for the embryonic phase in which the parasitization is performed. Parasitoid oviposition preference varies among host species and lineages [22]. Egg parasitoids perform several touches with the antennas on the egg surface, allowing the identification and detection of attributes that will contribute to qualify either the egg is a suitable host or if it was previously parasitized [23]. Some egg parasitoids species prefer hosts at the initial phase of embryonic development while others prefer more advanced embryonic stages, but there are parasitoids with no preference [24, 25].

Egg parasitoids, such as species from the Platygastridae family, are prominent as biological control agents and occur naturally on *Megacopta cribraria (*Hemiptera: Plataspidae) found in soybean fields in the U.S.A [26]. Natural occurrence of scelionids, such as *Telenomus triptus* (Hymenoptera: Scelionidae) and *Telenomus cyrus* (Hymenoptera: Scelionidae) in Asia and *Telenomus podisi* (Hymenoptera: Scelionidae) in southern Brazil have been reported as well [27, 28, 29]. According to Aquino *et al*. (2019) [30], in Brazilian soybean fields, 80 percent of naturally parasitized pentatomid eggs are *Euschistus heros* (Hemiptera: Pentatomidae). Similar was previously found by Riffel *et al*. (2010) [31] in egg masses of *Tibraca limbativentris* (Hemiptera: Pentatomidae) in irrigated rice fields.

4. Larval parasitoids

Larval parasitoids are widely used in biological control programs. The gender *Cotesia* spp. is the fourth most used taxon in augmentative biological control, especially in South America and China [3]. The use of larval endoparasitoids has been widely discussed in fruticulture but such a strategy is still poorly commercially explored. Even though, various larval parasitoids occur naturally in fruit flies, specially larvapupa koinobiont endoparasitoids [32].

Braconids prefer to parasitize fruit flies larvae at the third instar, however parasitization may occur at the first and second instar in a lower rate [33]. This preference is related to the searching ability of females, once parasitoids easily detect larger hosts inside the fruits [34]. For example, the braconid *Diachasmimorpha longicaudata* (Hymenoptera: Braconidae) prefers to parasitize third instar larvae of *Anastrepha fraterculus* (Diptera: Tephritidae) because it generates a larger number of adult parasitoids [35, 36]. A bigger host provides better nutritional conditions to meet the requirements for parasitoid offspring development.

For a successful applied biological control with parasitoid wasps, mass breeding must be efficient and uninterrupted, lasting several generations in the same host species. For example, the pupal parasitoid *Psyttalia concolor* (Hymenoptera: Braconidae) has been successfully bred for several generations in *Ceratitis capitata* (Diptera: Tephritidae) without any changes in the parasitoid efficiency [37]. Nevertheless, it should be kept in mind that ingredients of the diet in which the fly is reared have a direct influence on the quality of the parasitoid [38].

The most successful example of an applied biological control program is the case of the larval endoparasitoid *Cotesia flavipes* (Hymenoptera: Braconidae) for controlling the sugarcane borer *Diatraea saccharalis* (Lepidoptera: Crambidae). This biological control program was established in the 1970s in Brazil and has been applied in 40 percent of the sugarcane fields in that country [4, 21]. In addition, *C. flavipes* is commercially registered in Brazil (Table 1), stimulating the replacement of chemical products by this profitable option.

Table 1: Summary of the number of commercial parasitoids registered in Brazil (http://agrofit.agricultura.gov.br).

BCA	No. products	Targeted pest	Culture
Cotesia flavipes	27	*Diatraea saccharalis*	All
Trichogramma galloi	7	*Diatraea saccharalis*	All
Trichogramma pretiosum	8	*Tuta absoluta, Anticarsia gemmatalis, Spodoptera frugiperda, Helicoverpa zea*	All
Trissolcus basalis	1	*Nezara viridula*	All

5. Pupal parasitoids

Pupae parasitoids are important natural enemies for the balance in eucalyptus agroecosystem [39, 40]. *Palmistichus elaeisis* (Hymenoptera: Eulophidae) is a generalist pupal endoparasitoid with high potential for biological control of lepidopterans in eucalyptus [41]. Its parasitization has been verified in *Thyrinteina arnobia* (Lepidoptera: Geometridae), *Thyrinteina leucoceraea* (Lepidoptera: Geometridae), species of the genus *Hylesia* (Lepidoptera: Saturniidae) and others [41, 42]. However, lepidopterans have several defense mechanisms against parasitoid attacks. Soares *et al*. (2009) [43] reported that pupae of *T. arnobiae* and *Hylesia* sp., parasitized by *P. elaesis*, presented rotational abdominal movements to expel the parasitoid when it tried to oviposit.

6. Adult parasitoids

The parasitoid *Aphidius colemani* (Hymenoptera: Aphidiidae) is an aggressive control agent for aphids in diverse plant species. This species has shown to be resistant to methoxyfenozide and indoxacarb, being suitable for use in IPM systems [44]. Furthermore, plant fertilization may be helpful for parasitoids, e.g. adult emergence and longevity of *Aphidius rhopalosiphi* (Hymenoptera: Aphidiidae) is positively influenced by nitrogen fertilization on *Sitobion avenae* [45]. Even though, nitrogen fertilization presents a positive influence on phytophagous insects as well, but it depends on how the fertilizer is delivered to the plant [9, 46]. Thus, in terms of IPM and biological control, nitrogen fertilizers must be carefully managed to avoid pest insurgence.

Coleopteran parasitoids may be relevant for controlling important pests like curculionids. An important case of success has been recently described for controlling the South American weevil *Listronotus bonariensis* (Coleoptera: Curculionidae) with *Microctonus hyperodae* (Hymenoptera: Braconidae) in New Zealand [47]. The parasitoid was release into New Zeland in 1991 and suffered reproductive adaptations that allowed its successful establishment into the new environment.

7. Future perspectives and conclusions

The applied biological control has been largely used worldwide. Many cases of success, such as the Brazilian example, show that biological control with parasitoid wasps is a viable and ecofriendly option that can replace other methods of pest control. In addition, according to a recent review by van Lenteren *et al*. (2018) [3], several examples are likely to have great potential for inclusion in IPM. Unfortunately, even with developmental cost of biological control being cheaper and having a superior success ratio, the commercial use is still poorly explored compared to chemical control [12, 48]. For a better exploration of biological control agents, more investments by market players are urged, once a vast knowledge from the academy is available and under constantly maturation.

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