

PARASITIC INSECTS AND MITES AS POTENTIAL BIOCONTROL AGENTS FOR A DEVASTATIVE PEST OF TOMATO, *Tuta absoluta* Meyrick (LEPIDOPTERA: GELECHIIDAE) IN THE WORLD: A REVIEW

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ABSTRACT

The tomato leafminer *Tuta absoluta* is extremely difficult to control using chemical insecticides because larvae mine within plant tissue and are thus protected at least from contact insecticides. Also, larvae have an ability to develop resistance to insecticides and thus its control is quite challenging. Thus, parasitoids are a very important component of the natural enemy complex of *T. absoluta* and have been the most common type of natural enemies introduced for biological control of it. In the present review, the importance of different egg-, larval- and pupal-parasitoids, belonging to several insect orders and families, as well as some Pyemotidae mites, was discussed. Research efforts and application works for biocontrol of *T. absoluta* in European, North African and Middle East countries, as well as the native home, South American countries, had been reviewed. Some considerations were presented, such as the parasitism mechanisms, factors affecting the parasitic efficiency, interference or interaction between parasitoids and some other natural enemies, side-effects of synthetic and botanical pesticides on parasitoids and conservation of indigenous natural parasitoids of *T. absoluta*.

Keywords: *Efficiency, conservation, Hymenoptera, Diptera, Pyemotidae, interference, competitiveness.*

1. INTRODUCTION.

The tomato leafminer or American tomato pinworm, *Tuta absoluta* (= *Scrobipalpula absoluta* = *Scrobipalpuloides absoluta*) (Meyrick) (Lepidoptera: Gelechiidae), is a native devastating pest of South America, particularly to the tomato *Solanum lycopersicum* L. (or *Lycopersicon esculentum* (Mill.)) [1-4]. It may be described as an intercontinental pest. Although *T. absoluta* is an endemic Neotropical pest, it has acquired a wider geographical distribution after its unintended introduction in other tomato production regions [2, 5, 6]. Since its first detection in Europe in late 2006 (Iberian Peninsula) [5, 7], it has expanded very quickly during three years (2007-2009) to many countries in center and north Europe [8]. Moreover, it has become an economically important pest in the major tomato-producing countries in the Mediterranean Basin countries of Europe and North Africa [2, 9-15]. In addition, the pest was reported in several Middle East, African and Asian countries [16-21]. This pest causes a very high level of damage (quantity and quality) to tomato crops [22, 23], particularly if no control measures are adopted [16, 24, 25]. Beside tomato, *T. absoluta* is also able to attack and cause damage on different genera and species of the Solanaceae plants (eggplant, sweet pepper, potato and tobacco) [26]. In the Mediterranean basin, it infests also other plants [2].

The primary *T. absoluta* management strategy in most native home, South America, or invaded European and African countries, is chemical control [27-29]. However, pesticides are only partially successful because of the general endophytic behaviour of the larval instars [27, 30]. The resistance development in this pest to chemicals had been reported [24, 27-29, 31, 32]. Application of a pheromone-based mating disruption technique also provide poor results [33]. The prophylactic tools may be effective and eco-friendly way to control this invasive pest [34]. One explanation had been recently provided by the demonstration of a parthenogenetic reproduction in *T. absoluta*, from the research group in Gembloux Agro-Bio Tech (ULg) [35].

Because there is a real need to improve crop protection against *T. absoluta* and in the meanwhile reducing the use of synthetic insecticidal compounds, researches aim at providing new perspectives to further biocontrol strategies against *T. absoluta* [35]. Several biological control (BC) agents and integrated pest management (IPM) programs have been recently evaluated [36-38]. BC agents (living antagonists-natural enemies: predators, parasitoids and pathogens) are considered as one possible solution of the *T. absoluta* crisis [2, 39]. This strategy offers a more sustainable and less expensive alternative to chemicals [40-43].

A parasitoid is an organism that spends a significant portion of its life history attached to or within a single host organism in a relationship that is in essence parasitic; unlike a true parasite, however, it ultimately sterilizes or kills, and sometimes consumes, the host (for some details, see [44-46]). Parasitoids are a very important component of the natural enemy complex of insect pests and have been the most common type of natural enemy introduced for biological control of insect pests [47]. A number of parasitoids of leafminers have been recorded throughout the

world [48, 49]. A brief outlook of the future research and applications of indigenous *T. absoluta* biological control agents was provided [50]. Objective of the present review deals with the parasitic insects and mites as natural enemies and promising biocontrol agents against *T. absoluta* all over the major tomato-producing countries in the world. As necessary related aspects: parasitism mechanisms, factors affecting the parasitic efficiency, interference or interaction between parasitoids of *T. absoluta* and some other natural enemies, side-effects of synthetic and botanical pesticides on parasitoids of *T. absoluta* and conservation of indigenous natural parasitoids had been discussed.

2. PARASITIC INSECTS AGAINST *Tuta absoluta*.

Compared to larval and pupal parasitoids, egg parasitoids should be considered better, because if they are effective, they can rapidly reduce the commercial damage in the same way as insecticides; whereas the larval and pupal parasitoids will control the pest over time but attack the pest only once the damage has been done [51]. It is important to point out that no parasitoids of *T. absoluta* adults have been reported in the available literature. The parasitic insects, as natural enemies or biocontrol agents, with special emphasis on *T. absoluta*, can be reviewed herein according to the pest infested stage beside to the insect orders and families.

2.1. Egg parasitoids.

From the taxonomic point of view, all recorded egg parasitoids of *T. absoluta* have been belonged to the order Hymenoptera. However, virtually nothing is known about *T. absoluta* egg parasitoids belonging to other orders as seen in the literature. The most important *T. absoluta* egg parasitoids are found in the families Trichogrammatidae, Encyrtidae and Eupelmidae.

The **Trichogrammatidae** are a family of tiny wasps in the superfamily Chalcidoidea that include some of the smallest of all insects (for some information, see [52, 53]). Different Trichogrammatid species attack eggs of insects belonging to 11 orders, especially Hymenoptera, Neuroptera, Diptera, Coleoptera and Hemiptera [54]. *Trichogramma* (commonly known as stingless wasps) represent about 80 genera with over 800 species worldwide. They occur naturally in a variety of habitats across the world [55, 56]. There have been more than a thousand papers published on *Trichogramma* and their use as biological control agents in the world [57, 58]. Consoli et al. [59] edited a comprehensive book in which the egg parasitoids *Trichogramma* gained a considerable interest through both basic and applied information. About 210 species of *Trichogramma* are signaled as natural enemies of a variety of agricultural and forest pests in many regions of the world and at least 12 species are widely used commercially in biological control programs [60-65]. The *Trichogramma* parasitoids, as biocontrol agents, can be produced quickly and affordably relative to other parasitoids, due to the short generation time and the fact that they can be easily reared on factitious hosts [66]. Success in biological control by *Trichogramma* depends on the taxonomic identification of these species. Recently, a molecular techniques were developed to resolve the taxonomic status of these parasitoids [67-73].

Trichogramma pretiosum (Riley) is a more general parasitoid, by which it is likely to parasitize a range of different species [55]. The biological characteristics, thermal requirements and parasitism capacity of it had been studied on eggs of different lepidopterans [74-77]. This egg parasitoid wasp has been widely used to control *T. absoluta* [2, 24, 36, 41, 63, 78-92].

Trichogramma exiguum Pinto & Platner has a good parasitism efficiency against *Ephestia* (= *Anagasta*) *kuehniella* (Lepidoptera: Pyralidae) and *Sitotroga cerealella* (Lepidoptera: Gelechiidae) [93, 94]. Operational considerations for augmentation of this parasitic wasp was investigated for suppression of *Rhyacionia frustrana* (Lepidoptera: Tortricidae) [95]. Effects of some environmental factors on its development and adult survival had been studied [96, 97]. This egg parasitic wasp was reported as biocontrol agent against *T. absoluta* [2, 24, 98].

Trichogramma achaeae Nagaraja & Nagarkatti has a worldwide distribution [99]. It is an egg parasitoid of 26 Lepidoptera species belonging to 10 families and has been evaluated as a biological control agent of different lepidopteran pests [91, 100-103]. This parasitic wasp was observed parasitizing on *T. absoluta* and may be a potential parasitoid for controlling it [2, 24, 88, 104-117].

Trichogramma evanescens Westwood can taxonomically considered as a synonym of *Trichogramma turkestanica* Meyer [118] or *Trichogramma euproctidis* Girault [119, 120]. Sequence of the behavioral events and progeny production [121], as well as the dispersal ability and parasitization performance [122-124] of *T. evanescens* had been investigated. This egg parasitoid was used to control *T. absoluta* [24, 39, 111, 125, 126]. Several biological and ecological studies of *T. turkestanica* had been carried out [119, 127-130]. The latter egg parasitoid was recorded on or used to control *T. absoluta* [125]. Some studies had been carried out on mating behaviour [131], feeding behaviour [132] of *T. euproctidis*. In addition, the effect of host availability on the biology [133] as well as the effect

of ionizing (Gamma) and non-ionizing (UV) radiation on the development [134] were studied. The latter parasitoid wasp was recorded on or used to control *T. absoluta* [111, 116].

Trichogramma bourarachae Pintureau & Babault gained some research attention to investigate its biological potentialities [135], the potential effect of flowering plants on its activity [136], parasitism rate [137] and effects of some synthetic pesticides and biopesticides [138]. It was tested against some lepidopterous insect pests in Sudan [139]. This egg parasitoid has been used for controlling *T. absoluta* [73, 111, 125].

Trichogramma cacoeciae Marchal was used as an indicator species for testing the side-effect of pesticides on beneficial arthropods [140]. Also, temperature-dependent differences in biological traits between two strains of *T. cacoeciae* [141], the parasitization rate [142] and field release as a part of biological control of codling moth, *Cydia pomonella* (Tortricidae, Lepidoptera) [143] had been investigated. This egg parasitoid has been used to control *T. absoluta* [24, 144-146].

Trichogramma cordubensis Vargas & Cabello was used as a biological control agent for agricultural pests existing in the Azores islands had been studied [147, 148]. Host suitability [149] and the effect of female age on the parasitization capacity [150] of this parasitoid had been studied. Trials for using this parasitoid to control *T. absoluta* had been conducted [125].

Trichogramma pintoï Voegele was reported as an egg parasitoid on *Lobesia* spp. (Lepidoptera: Tortricidae) in Ukraine [151], on winter moth *Operophtera brumata* (Lepidoptera: Geometridae) in Iran [152], on *P. xylostella* [153] and on some other lepidopterans [154]. Iannacone and Lamas [155] evaluated the toxicity of certain plant extracts on *T. pintoï* in Peru. This egg parasitoid was observed on or used to control *T. absoluta* [2, 24, 125].

Trichogramma minutum Riley is one of the most commonly egg parasitoids found in Europe [54]. It is used throughout North America for the biological control of lepidopterous orchard and forest pests [156]. Its parasitism role was studied [157-159]. As early as 1965, *T. minutum* was collected from Peru for using against *T. absoluta* in Chile [160]. The same egg parasitoid was recorded on the present pest in some other South American countries [2] and Turkey [24].

Trichogramma brassicae Bezdenko is used worldwide for the control of lepidopterous pests. It acts as an egg parasitoid of the carob moth, *Apomyelois (Ectomyelois) ceratoniae* (Lepidoptera: Pyralidae), in Iranian pomegranate orchards [161]. Kuske et al. [162] evaluated the effects of inundative releases of *T. brassicae* against the European corn borer, *Ostrinia nubilalis* (Lepidoptera: Crambidae). This egg parasitoid may attack *T. absoluta* [163].

Trichogrammatoidea bactrae Nagaraja is an egg parasitoid of the pink bollworm, *Pectinophora gossypiella* (Lepidoptera: Gelechiidae) in Australia [164]. Some behavioural responses [165, 166], its viability at different temperatures [167] and parasitization [168] were determined. This egg parasitoid had been recorded on or used to control *T. absoluta* [2, 24, 88, 169-172].

Trichogramma dendrolimi Westwood, was reared on eggs of a factitious host, *Antheraea pernyi* (Lepidoptera: Saturniidae) [173]. Its host-acceptance behaviour is plastic [174]. Several factors affecting its parasitization capacity to eggs of some lepidopterans had been investigated [142, 175]. This egg parasitoid had been recorded on or used to control *T. absoluta* [2, 24].

Trichogramma fasciatum (Perkins) was released to control the sugarcane borer *Diatraea saccharalis* (Lepidoptera: Crambidae) [176]. Among the most common parasitoids of *Epiphyas postvittana* (Lepidoptera: Tortricidae) in San Francisco Bay Area (USA) was *T. fasciatum* [177]. This egg parasitoid had been recorded on or used to control *T. absoluta* [2, 24].

Trichogramma lopezandinensis Sarmiento was recovered from eggs of the butterfly *Colias dimera* (Lepidoptera: Pieridae) in Colombia and was reared on *Sitotroga cerealella* (Lepidoptera: Gelechiidae) in the laboratory [178]. Some studies were carried out to use it for the control of potato tuber moth *Tecia solanivora* (Lepidoptera: Gelechiidae) [179, 180]. This egg parasitoid had been recorded on or used to control *T. absoluta* [2, 24].

Trichogramma nerudai Pintureau and Gerding exhibited no preference for any of some lepidopterous pests [181]. In contrast, it may be useful in biological control programs of forest and agricultural insect pests, such as some lepidopterans, in several South America countries [182] and in Sudan [139]. This egg parasitoid could be used to control *T. absoluta* [2, 24, 183, 184].

Trichogramma rojasi Nagaraja and Nagarkatti was reported as a biocontrol agent opening perspective to integrate biological control programs of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in Cuba [185]. Also, *T. rojasi* was collected from eggs of *Anticarsia gemmatalis* (Lepidoptera: Noctuidae) in Southern Brazil [186]. This egg parasitoid had been recorded on or used to control *T. absoluta* [2, 24].

Trichogramma telengai Sorokina was recorded as an egg parasite of *Tortrix viridana* (Lepidoptera: Tortricidae) in the oak forests of the Crimea [187]. Recently, the maternal and grand-maternal photoperiodic responses of *T. telengai* were investigated in laboratory conditions [188]. This egg parasitoid had been recorded on or used to control *T. absoluta* [2, 24]. In addition, *Trichogramma urquijoi* Cabello Garcia had been reported as an egg

parasitoid for *Heliothis armigera* (Lepidoptera: Noctuidae) [189]. It was recorded on or used to control *T. absoluta* [108, 109].

Family **Encyrtidae** is one of the largest families in the superfamily Chalcidoidea (order Hymenoptera) and comprise about 3735 recognized species in 460 genera [190]. They are found throughout the world in virtually all habitats. All species are parasitoids but they are known to attack at least 153 insect families and 8 families of other arthropods. About 250 species of encyrtids have been used in biocontrol programmes involving nearly 150 pest species [191, 192].

A mass release technique of the egg parasitic microwasp *Copidosoma koehleri* Blanchard on the potato moth *Phthorimaea operculella* (Lepidoptera: Gelechiidae) was developed [193]. The parasitism potential of this parasitoid on the same lepidopteran pest had been evaluated [194-196]. This egg parasitoid was observed on or used for control *T. absoluta* [2, 24, 197, 198].

The microwasp *Copidosoma desantisi* Annecke & Mynhardt was observed as a parasitoid of *Ph. operculella* on potato foliage in south-eastern Queensland [199] and Egypt [124, 200]. Its longevity and fecundity on *Ph. operculella* [201] and the parasitization efficiency [202] had been evaluated. It is one of egg parasitoids attacking different developmental stages of *T. absoluta* in South America [2, 24].

The parasitoid *Arrhenophagus* sp. was reported as a biocontrol agent for *Pseudaulacaspis pentagona* (Hemiptera: Diaspididae) in Hungary [203]. *Arrhenophagus albitibiae* Girault was recorded as natural parasite of *Aleurodicus dispersus* (Homoptera: Aleyrodidae) in Guam (western Pacific Ocean) [204]. Another parasitoid species in this genus, *Arrhenophagus chionaspidis* Aurivillius, was observed on *Aulacaspis yasumatsui* (Homoptera: Diaspididae) in Indonesia [205]. *Arrhenophagus* sp. was recorded on or used to control *T. absoluta* [2, 24].

Family **Eupelmidae** (order Hymenoptera) includes flightless parasitoid wasps of more than 905 described species in 45 genera. The larvae of the majority are primary parasitoids, commonly on beetle larvae, though many other hosts are attacked, including spiders. They are found throughout the world in virtually all habitats [206-209]. The parasitic wasp *Anastatus* sp. was reported on various lepidopteran and hemipterans in different parts of the world [210-213]. Also, it was recorded as an egg parasitoid on or used for controlling *T. absoluta* [2, 24].

2.2. Larval parasitoids.

There is a large body of literature on the larval parasitoids of *T. absoluta* as classified in two insect orders, Hymenoptera and Diptera. With regard to Hymenoptera, different families (Encyrtidae, Eulophidae, Braconidae, Bethyridae, Chalcididae, Torymidae, Pteromalidae and Ichneumonidae) include several larval parasitoids while Tachanidae is only the family in order Diptera including some larval parasitoids of the present tomato leafminer.

2.2.1. Hymenoptera.

In the family **Encyrtidae**, *Copidosoma* sp. was reared from larvae of *T. absoluta* collected in Argentina [214]. The absolute and relative preferences of the parasitoid *C. koehleri* on *T. absoluta*, tuber moth *Ph. operculella* and tomato stemborer *Symmetrischema tangolias* (Lepidoptera: Gelechiidae) were evaluated. Clear preference was observed for *Ph. operculella* but a minimum parasitism for *T. absoluta* [215]. *Copidosoma* sp., as a larval parasitoid, may be used to control *T. absoluta* [198, 214, 215].

Family **Eulophidae** represents the largest one within the parasitic Hymenoptera, superfamily Chalcidoidea. Currently the family is represented by at least 4472 described species in 297 genera [216]. The majority are primary parasitoids on a huge range of arthropods at all developmental stages. Several species of Eulophidae are important in biocontrol programs throughout the world [217].

The genus *Necremnus* contains 30 species [218] and comprises ectoparasitoids of lepidopterous larvae and of coleopterous larvae and prepupae [219]. The wasp *Necremnus tidius* (Walker) was recorded as a solitary ectoparasitoid of the cabbage seedpod weevil *Ceutorhynchus obstrictus* (Coleoptera: Curculionidae) in western Canada [220-222]. This wasp was used as a larval parasitoid to control *T. absoluta* [2, 38, 223, 224-226, 112, 227]. *Necremnus arynes* (Walker) is a biparental generalist solitary ectophagous parasitoid of lepidopteran leafminers. It has been reported over all Mediterranean countries [228-230]. It was reported as a larval parasitoid for controlling *T. absoluta* [2, 14, 15, 24, 38, 50, 112, 223, 224, 226, 228, 230-234].

The wasp *Chrysocharis pentheus* (Walker) was reported as both predator and parasite on the agromyzid pea pest *Phytomyza horticola* (Diptera: Agromyzidae) [235]. As a natural parasite, it attacks the larvae of *Liriomyza trifolii* (Diptera: Agromyzidae) [236]. The same parasitic wasp had been recorded as a biocontrol agent against *T. absoluta* [225].

Wasp species of the genus *Pnigalio* are ectoparasitoids, with solitary or gregarious larval development. Most of them are polyphagous and potentially important for biological control of lepidopterous leaf miners [237]. The wasp *Pnigalio soemius* (Walker) (= *Pnigalio flavipes* = *Eulophus flavipes* = *Pnigalio punctiscuta*) is an ectoparasitoid of 89 leaf miner species and larvae of gall-makers from several insect orders [2, 238, 239]. The same parasitic wasp

was recorded as biological control agent for *T. absoluta* [2, 38, 225]. In addition, other parasitic wasps of *Pnigalio*, such as *Pnigalio* (= *Ratzeburgiolo*) *christatus* (Ratzeburg) and *Pnigalio* (= *Ratzeburgiolo*) *incompletes* (Boucek), had been used to control *T. absoluta* [24, 38, 225, 240]. Recently, *Pnigalio* sp. was recorded on *T. absoluta* only at Mostaganem in Algeria [15].

The wasp *Hemiptarsenus zilahisebessi* Erdős had been reported as a parasitoid of leaf miners from orders Coleoptera, Lepidoptera and Diptera. *H. zilahisebessi* was identified as a parasitoid of leaf miners, *Liriomyza sativae* [241] and *L. trifolii* [242] in Iran. The same parasitic wasp was assessed as biological control agent against *T. absoluta* [15, 24, 228, 243].

Tetrastichus planipennis Yang is a gregarious larval endoparasitoid wasp which is native to North Asia. It is a parasitoid of the emerald ash borer *Agrilus planipennis* (Lepidoptera: Buprestidae) in North America [244, 245]. In addition, *Tetrastichus howardi* (Olli) is a gregarious pupal parasitoid which has been recorded as a primary parasitoid or facultative hyperparasitoid associated with a great number of Lepidoptera pests of important crops [246, 247]. *Tetrastichus* sp. was recorded as a larval parasitoid on or used to control *T. absoluta* [24].

More than 119 species in the large genus *Sympiesis* worldwide are mainly ectoparasitoids, hyperparasitoids, or larval and pupal parasitoids of various species of Lepidoptera, Coleoptera, and Diptera [218]. *Sympiesis striatipes* Ashmead is one of the most abundant ectoparasitoid on the gracillariid leafminers *Acrocercops* sp. and *Phyllonorycter* sp. in several Asian countries [248] and the citrus leafminer *Phyllocnistis citrella* (Lepidoptera: Gracillariidae) in Japan [249]. However, *Sympiesis* sp. was observed as a larval ectoparasitoid on or used to control *T. absoluta* [2, 230].

Biology [250] and eco-biology [251, 252] of the larval parasitoid *Diglyphus isaea* (Walker) were studied. *D. isaea* is a primary parasitoid on agromyzid leaf miners and has been commercialized as a biological control agent [253-255]. This larval parasitoid was used to control *T. absoluta* [15, 230]. In addition, *Diglyphus crassinervis* Erdős was recorded among parasitoids attacking the agromyzid leafminer flies [256]. The latter parasitoid was reported as a biocontrol agent against *T. absoluta* [225].

The naturally occurring larval ectoparasitoid *Dineulophus phthorimaeae* de Santis has been reported to have potential biocontrol efficiency in Argentina and Chile [257]. This larval ectoparasitoid was reported as natural enemy to control *T. absoluta* [2, 24, 257-261].

Neochrysocharis (Clostrocercus) formosa (Westwood) is now known from all continents except Australia, and has an extremely varied biology [190]. It is currently considered cosmopolitan after several introductions for biological control of more than 100 species in many orders, Coleoptera, Hemiptera, Diptera, Lepidoptera, and Hymenoptera [262, 263, 264]. It was registered as a biological control agent for agromyzid leafminer pests [265, 266]. Several works had been achieved to use this parasitoid for controlling *T. absoluta* [2, 14, 15, 19, 24, 38, 225, 260, 267].

Some aspects of a native *Tetrastichus* sp. parasitic on the chondrilla gall midge *Cystiphura schmidtii* (Diptera: Cecidomyiidae) were described in Australia [268]. Its impact on the host and potential biological control was evaluated [269]. The wasp *Tetrastichus* sp. was recorded as a larval ectoparasitoid on *T. absoluta* [2].

The parasitoid *Zagrammosoma* sp. was collected from the lemon leaves infested with citrus leafminer, *Ph. citrella* in the Central Jordan Valley [270]. Also, it was recorded among parasitoids that associate with the leafminer fly, *L. sativae* found on lowland vegetables ecosystem in South Sumatra [271]. This larval parasitoid was recorded on *T. absoluta* [2, 24].

Stenomiesius spp, and mainly *Stenomiesius japonicus* (Ashmed), have a wide host range including Gelechiidae, Pyralidae and Gracillariidae [272]. *Stenomiesius* sp. had been reported spontaneously attacking *T. absoluta* in infested tomatos [14, 15, 273]. *Stenomiesius* sp. near *japonicus* was recorded parasitizing *T. absoluta* [274].

As ectoparasitoids on *T. absoluta*, several other eulophids were reported, such as *Horismenus* sp. [2], *Baryscapus bruchophagi* (Gahan) [24, 240], *Retisympiesis phthorimaeae* Blanchard [2, 24, 39], *Cirrospilus* sp. [275, 276], *Elachertus inunctus* Nees [2], *Closterocercus clarus* (Szelenyi) [24, 240] and *Elasmus* sp. [2].

The **Braconidae** is a family of parasitoid wasps [277] and is one of the largest families in order Hymenoptera [278, 279]. Braconid wasps are cosmopolitan and diverse in all areas [280] but they are highly abundant in cool temperate regions [281]. Most braconids are primary endoparasitoids of Lepidoptera larvae, although most holometabolous groups may be attacked. They have important role in the biological control of the phytophagous insect pests, particularly the economically important pests [282-284].

The braconid wasp *Bracon nigricans* Szépliget is a larval ectoparasitoid of Lepidoptera species. The acute toxicity and sublethal effect of six bioinsecticides, used for controlling *T. absoluta*, were assessed on the fertility of *B. nigricans* [295]. The available literature contains other reports of its use to control the same pest [24, 38, 225, 274, 296].

The braconid wasp *Bracon (Habrobracon) hebetor* Say is a gregarious larval ectoparasitoid of several species of Lepidoptera that are associated with stored products [297]. Some attempts to develop an alternative system to mass

rear this parasitoid were achieved [298, 299]. This parasitoid wasp was observed on or used to control *T. absoluta* [14, 19, 24, 225, 240].

The parasitic wasp *Bracon (Habrobracon) concolorans* (Marshall) has generally been referred to as *H.* (or *B.*) *nigricans* (Szepligeti) but recently the name *nigricans* has been synonymized under *concolorans* [300]. *B. concolorans* is known from a wide range of countries from western and southern Europe east to Russia (Primorsky) and China. It was found also in Tunisia, Iran and Turkey (for details, see [300]). It is recorded from Jordan [300] and Sudan [19] for the first time, attacking *T. absoluta*.

Also, other *Bracon* species, such as *Bracon lulensis* Berta & Colomo [2, 80, 301, 302], *Bracon tutus* Berta & Colomo [2, 24, 80, 301, 302], *Bracon lucileae* Marsh [2, 24, 80, 301-303], *Bracon (Glabrobracon) osculator* Nees [24, 38, 225] and *Bracon didemie* Beyarslan [24, 240, 304] had been recorded among parasitoids attacking *T. absoluta* and can be used to control it.

All species of the genus *Agathis* are solitary koinobiont endoparasitoids of many concealed Lepidopterous larvae [305]. *Agathis fuscipennis* (Zetterstedt) (= *Agathis glabricula* Thomson) is a polyphagous parasitoid living on many Lepidoptera families [305, 306]. *A. fuscipennis* was observed as larval parasitoid on *T. absoluta* [2, 225, 307].

The wasp *Chelonus* sp. is an egg-larval parasitoid of the cabbage looper *Trichoplusia ni* (Lepidoptera: Noctuidae). Some biological [308], physiological [309] and parasitization [310] studies of this parasitoid had been carried out. This wasp was recorded as a larval parasitoid on *T. absoluta* and can be used to control this pest [2, 301, 302].

Earinus sp. was observed among three species parasitizing apple leafroller *Bonagota cranaodes* (Lepidoptera: Tortricidae) in southern Brazil [311]. It was collected from the quinoa moth *Eurysacca melanocampta* (Lepidoptera: Gelechiidae) [312]. Also, it was observed as a natural larval parasitoid of *T. absoluta* and may be used to control this pest [2, 24, 313, 314].

Based on the characteristics of fecundity, daily oviposition and longevity, the braconid *Orgilus* sp. can be used for the control of *Ph. operculella* [315]. It was recorded as a larval parasitoid on *T. absoluta* and its release to control this pest is feasible [2, 24, 301, 302].

Some other wasps in the family Braconidae had been recorded on or used to control *T. absoluta*, such as: *Apanteles gelechiidivoris* Marsh [2, 316-318], *Apanteles dignus* Muesebeck [2, 319], *Pseudapanteles dignus* (Muesebeck) [2, 24, 230, 321, 260, 322-325] and *Dolichogenidia gelechiidivoris* [326]. In addition, three Argentina species of *Bracon* (*B. lulensis*, *B. tutus*, *B. lucileae*) parasitize larvae of *T. absoluta* [301].

The **Bethylidae** are a family of aculeate wasps (order Hymenoptera) widely distributed throughout the world, but the majority of species occur in tropical regions. The family comprises about 100 genera and about 2400 described species [327]. Bethyloid species have attracted the attention of applied entomologists because their hosts (larvae, and more rarely pupae, of Lepidoptera and Coleoptera) include many important pests of crops and stored products [328]. Some of biological aspects of *Parasierola (Goniozus) nigrifemur* Ashmead were studied [329, 330]. This parasitoid wasp was observed on or used to control *T. absoluta* [2, 24, 80].

The family **Chalcididae** (order Hymenoptera) is cosmopolitan in distribution, and particularly diverse in tropical lowland areas. It comprises about 1500 species in nearly 90 genera [331]. All Chalcididae are parasitoids of larvae or pupae of other insects, such as Lepidoptera, Diptera, Coleoptera, Neuroptera, and Hymenoptera [332]. *Brachymeria* is a genus of chalcidid parasitic wasps. All species are parasites of insect larvae. The chalcid wasp *Brachymeria secundaria* (Ruschka) was observed as a larval parasitoid on *Malacosoma neustria* (Lepidoptera: Lasiocampidae) in Turkey [333]. This chalcid parasitic wasp was reared from mines of *T. absoluta* and it may be primary and secondary parasitoid of this pest [240]. The wasp genus *Haltichella* currently includes about 20 species parasitizing Lepidoptera pupae in the Neotropics [334]. *Hockeria unicolor* (Walker) is common and widely distributed in the Palaearctic region from Canary Islands to Central Asia [335]. It is known as a pupal parasitoid of microlepidoptera of the families Tortricidae, Cosmopterigidae and Pyralidae [336] but it was reared from larvae in mines of *T. absoluta* on tomato [240] and observed attacking larvae of this pest [337].

The **Torymidae** are a worldwide family of wasps (order: Hymenoptera) containing over 960 species in about 70 genera [329]. Torymines are diverse biologically but most are ectoparasitic upon larvae in galls formed by gall-forming insects, as well as Hymenoptera and Diptera and a few families of Coleoptera and Lepidoptera [340]. Members of the genus *Ecdamua* are reported to be parasitic on aculeate Hymenoptera nesting in holed dead wood [340]. So far six species, including *Ecdamua cadenati* (Risbec), are reported from different parts of the world [341] and four parasitoids were observed on *T. absoluta* in Kassala State, Sudan among which was *E. cadenati* [19].

The **Pteromalidae** are a very large family (order Hymenoptera) of cosmopolitan small parasitic wasps which involves over 3506 species in 587 genera worldwide [342]. They are mostly primary parasitoids, but some are hyperparasitic; some are ectoparasitoids, whereas others are endoparasitoids. Pteromalids have considerable importance for the biological control of Lepidoptera, Coleoptera, synanthropic Diptera and Coccidae (Homoptera) [343, 344]. Species of the genus *Halticoptera* are known as parasitoids of mining Diptera associated with herbaceous plants or ferns [345]. The pteromalid *Halticoptera aenea* (Walker) was recorded as an endoparasitic

wasp of *T. absoluta* [24, 38, 225]. Another pteromalid wasp, *Pteromalus intermedius* (Walker), was collected from the same pest and may be used to control it [24, 240].

The **Ichneumonidae** (order Hymenoptera) is one of the most species rich families of all organisms with more than 60000 species in the world. Ichneumon wasps are important parasitoids of other insects. Common hosts are larvae and pupae of Coleoptera, Hymenoptera, and Lepidoptera. They have been used successfully as biocontrol agents of pests in these orders (for detail, see [346-350]). Parasitism of several species in the genus *Diadegma* was reported on different lepidopterous hosts [351-356]. *Diadegma pulchripes* (Kokujev) is known as larval parasitoids of Lepidopterans [357]. This ichneumonid wasp was described as a larval endoparasitoid on *T. absoluta* in South America [2], Turkey [24] and Mediterranean area [38]. Another species of this genus, *Diadegma ledicola* Horstmann, was recorded as an indigenous natural enemy in the Mediterranean area and has a potential role in reducing population of *T. absoluta* [50, 225]. The ichneumonid parasitic wasp *Pristomerus* sp. was reared from larvae of the avocado fruit borer *Stenoma catenifer* (Lepidoptera: Elachistidae) in Guatemala [358] and was observed on *Gymnandrosoma aurantianum* (Lepidoptera: Tortricidae) in Costa Rica [359]. This ichneumonid wasp was identified as a larval endoparasitoid on *T. absoluta* in South America [2] and Turkey [24]. Another ichneumonid wasp, *Temelucha* sp., was recorded as a larval parasitoid of *Spodoptera exigua* (Lepidoptera: Noctuidae) in Sekinchan, Selangor, Malaysia [360] and *L. botrana* in Orumieh vineyards in Iran [361]. The latter wasp was identified as a larval endoparasitoid on *T. absoluta* in South America [2] and Turkey [24].

2.2.2. Diptera.

Tachinidae is a large and rather variable family of true flies within order Diptera in the world [362] with more than 8200 known species and many more to be discovered [363]. All tachinids are parasitoids of other arthropods, ranging from caterpillars, the most common hosts, to spiders and scorpions [364]. The tachinids *Archytas* sp. *Elfia* sp. were recorded as a larval endoparasitoids of *T. absoluta* [2, 24].

2.3. Larval/pupal parasitoids.

2.3.1. Hymenoptera.

The braconid wasps *B. didemie* [240, 365] and *B. osculator* [38, 225] had been reported as larval/pupal parasitoids of *T. absoluta*. The wasp *Orgilus* sp. was recorded as larval/pupal parasitoid of *T. absoluta* [198]. Another braconid larval/pupal parasitoid, *P. dingus*, was assessed as a biocontrol agent for *T. absoluta* under laboratory conditions in Argentina [320, 322]. The eulophid wasp *Galeopsomya* sp. was recorded as a fortuitous parasitoid of the citrus leafminer, *Ph. citrella* [366]. It was observed as larval/pupal parasitoid on *T. absoluta* [198]. The wasp *H. zilahisebisi* was previously mentioned as larval parasitoid on *T. absoluta*, it was observed also as larval/pupal parasitoid on the same pest [104]. In addition, *Elasmus* sp. was recorded as larval/pupal parasitoid for *T. absoluta* beside its parasitism as larval parasitoid on the same pest [24]. The ichneumonid wasp *Campoplex haywardi* Blanchard is a solitary internal parasite of larvae of the potato tuberworm, *Ph. operculella* [367]. *C. haywardi* was identified as a larval/pupal endoparasitoid on *T. absoluta* in South America [2, 275] and Turkey [24].

2.3.2. Diptera.

In **Tachinidae**, *Archytas marmoratus* (Townsend) is a solitary larval-pupal parasitoid of numerous species of Noctuidae (Lepidoptera) [368-371]. It did not recorded as larval-pupal parasitoid of *T. absoluta* but *Archytas* sp. and *Elfia* sp. were recorded as larval endoparasitoid of this pest.

2.4. Pupal parasitoids.

Little records are available in the literature for the pupal parasitoids of *T. absoluta* inspite of their regular role to surpass the pest population [2]. This may a signal to urgent need for futher research in future. However, the reported pupal parasitoids as biocontrol agents for *T. absoluta* systematically belong to order Hymenoptera. In addition to their role as larval parasitoids in the biological control of *T. absoluta*, the following braconid wasps hand been reported also as pupal parasitoids on the same pest: *B. lulensis* [2, 301, 302], *B. tutus* [2, 24, 301, 302] and *B. lucileae* [2, 24, 80, 301, 302]. In addition to their role as larval parasitoids in the biological control of *T. absoluta*, the ichneumonod wasps, *D. pulchripes* [38, 225] and *D. leicole* [372], had been reported also as pupal parasitoids on the same pest.

In **Chalcididae**, *Conura* (syn. *Spilochalcis*) is primarily a New World genus with probably over 1000 species in the Neotropics which are pupal parasitoids of Lepidoptera, Diptera, Coleoptera, and Hymenoptera [334]. *Conura* sp. was recorded as a pupal parasitoid on or used to control *T. absoluta* [2, 24, 198, 302, 314]. The chalcidid wasps *Haltichella* spp. are mostly parasite of Microlepidoptera, some are hyperparasitoids of the family Braconidae and others are regarded as parasitoids of Diptera (Glossinidae) in Africa [373]. The same chalcidid wasp was reported as pupal parasitoid on *T. absoluta* [337]. The chalcidid wasp *Spilochalcis* sp. was reported as a parasitoid attacking the

sesame leafroller, *Antigastra catalaunalis* (Lepidoptera: Pyralidae) in Colombia [374]. This wasp was reported as pupal parasitoids on *T. absoluta* [337]. The greatest incidence of parasitism of the lesser cornstalk borer, *Elasmopalpus lignosellus* (Lepidoptera: Phycitidae), was found by the chalcidid wasp *Invreia* sp. in Oklahoma (USA) [375]. It was also reported as a parasitoid attacking honeydew moth, *Cryptoblades gnidiella* (Lepidoptera: Pyralidae) in the Eastern Mediterranean Region [376]. This wasp was recorded as a pupal parasitoid on *T. absoluta* [2, 24]. It may important to mention that *Invreia* sp. is treated as a synonym of *Psilochalcis* sp. [377]. As the chalcid wasp *B. secundaria* was aforementioned as larval parasitoid on *T. absoluta*, it was also observed as pupal parasitoid on the same pest [24]. Another chalcid wasp, *H. unicolor*, was reported as a pupal parasitoid on *T. absoluta* [24] as previously discussed as a larval parasitoid on the same pest.

3. PARASITIC MITES AGAINST *T. absoluta*.

Pyemotidae mites are widespread species and have been reported as ectoparasites of a large number of arthropods, especially of insects. They are parasites of all developmental stages of holometabolous insects, especially forest insects and stored product insects [378]. Species of the genus *Pyemotes* (Acari: Actinedida: Pyemotidae) might be considered as potential tools in biological control programs. The insect hosts of the parasitic mite *Pyemotes ventricosus* (Newport) were described [379]. More than 100 insect species are known as hosts of the mite *Pyemotes tritici* (Lagrèze-Fossat and Montagné) among Coleoptera, Hymenoptera, Lepidoptera, Homoptera, Strepsiptera and Diptera, but it is primarily associated with Coleoptera and Lepidoptera [94, 380]. In most cases, it was found on rearing mass in laboratories and stored products, attacking larval stages of some lepidopteras and coleopterans as well as adults of some coleopterans [381-384]. This mite can tightly attach to the host body and paralyze it, by injecting venom (toxins) [385]. However, *Pyemotes* sp. or *P. tritici*, was observed attacking *T. absoluta* [2, 39, 384, 386].

4. AN INSIGHT FOR THE PARASITIDS AS PROMISING BIOCONTROL AGENTS AGAINST *T. absoluta* IN DIFFERENT PARTS OF THE WORLD.

The development of approaches to manage *T. absoluta* in European, North African and Middle East countries depends on several factors. Many works were initiated on its control and much still remains to be done [15]. Taking into consideration the parasitic insects and mites, as natural enemies and biocontrol agents, especially against *T. absoluta*, it is important to review herein the available recent works in different parts of the world, particularly the invaded European, North African and Middle East countries as well as the origin of this pest, South American countries.

4.1. European, North African and Middle East countries.

Possible use of the egg parasitic wasps of *Trichogramma* genus, as biological control agents against *T. absoluta*, is currently considered in Europe [38, 43, 111]. Chailleux et al. [116] compared the efficiency of 29 *Trichogramma* species and strains in parasitizing *T. absoluta* eggs on tomatoes at three different scales. In respect to the larval parasitoids, a scientific basis for the inclusion of the parasitoid *B. nigricans* in *T. absoluta* management programs was provided in Afro-Eurasia [296]. The larval parasitoids *N. artynes* and *N. tidius* are naturally occurring in the Mediterranean basin and they had been evaluated for suppressing the severe infestations of *T. absoluta* in southern Europe [2]. Recently, the suitability of different instars of *T. absoluta* as hosts for *N. artynes* was evaluated at three different temperature regimes (20, 25 and 30°C) [387]. However, the biocontrol of *T. absoluta* by parasitoids in some important tomato-producing countries can be reviewed herein in some detail.

In **Spain**, suppression of *T. absoluta* infestations on the tomato plant can be given by parasites such as *Trichogramma* spp., *H. zilahisebessi*, *Necremnus* spp. and *Diadegma leicole* [231, 243]. The egg parasitoid *T. achaeae* had been identified as a candidate for biological control of *T. absoluta* in greenhouses of the southeast of Spain [91] and is currently being released in commercial tomato greenhouses [106, 273]. The biotic potential of *T. achaeae* and *T. urquijoi* for the control of *T. absoluta* was evaluated [109]. As a result, *T. achaeae* was found better at controlling pest populations than any other species. Prospecting for potential natural enemies of *T. absoluta* in the Canary Islands archipelago, new *Trichogramma* species, *T. achaeae*, *T. bourarachae*, *T. euproctidis* and *T. evanescens*, were identified [111]. An alternative release method for *N. tenuis* and its combination with *N. artynes* in Spain was investigated [113]. Also, *Stenomesus* sp. occurs spontaneously in infested tomato plots in Spain, indicating that native parasitoids are adapting to the new host [273].

In **Italy**, during the years following the first report of *T. absoluta*, several indigenous generalist parasitoids had been recorded on this new host. Among these, only a few have been identified as potential biological control agents [38, 225, 388]. During the period 2009-2010, nine species of indigenous parasitoids were collected from tomato leaves, infested by *T. absoluta*, in Liguria, Sardinia and Sicily. *N. artynes* and *N. tidius* were the most abundant species which appeared to be promising as biological control agent [226, 227]. The parasitoid *D. phthorimaeae* proved to be

a biocontrol agents against *T. absoluta* [260]. *A. fuscipennis* was collected from larvae of *T. absoluta* infesting *Solanum nigrum* plants in Tuscany (Central Italy) [307]. *B. nigricans* proved to be an ectoparasitoid of *T. absoluta* 3rd and 4th instar larvae [389].

In **France**, sixty-four new potential strains from 19 *Trichogramma* species originating from different regions of the world had been studied [390]. During the seasons 2011 and 2012 in Southern France, eggs of *T. absoluta* were attacked by *T. achaeae* whereas the larvae were parasitized by four parasitoid species, *B. nigricans*, *N. formosa*, *S. japonicus* and *N. artynes* [274]. As concluded by a research project of Wageningen UR Greenhouse Horticulture in **The Netherlands**, two ectoparasitic wasps, *E. inunctus* and *P. soemius* had been developed successfully on *T. absoluta* [2]. The suitability of different instars of *T. absoluta* as hosts for the parasitic wasp *N. artynes* was studied [387]. In **United Kingdom**, the egg parasitoid *T. achaeae* was found as an effective control agent for *T. absoluta*. In addition, two parasitoids, *N. artynes* and *H. zilahisebisi*, had been detected on *T. absoluta* larvae but it remains to be seen whether they have value as biological control agents [104]. In **Belgium**, the Palaearctic parasitoid *N. artynes* had been shown to attack *T. absoluta* in the fields, but its parasitism is generally low. A study was carried out to determine the impact of non-host resources on host-parasitoid interactions and the potential for using selective food resources in conservation biological control of *T. absoluta* [233]. Doganlar and Yigit [240] studied the parasitoid complex of *T. absoluta* in Hatay (**Turkey**). In the greenhouse of the University, 9 parasitoid species from 4 families of Hymenoptera were obtained. Thereafter, several species of parasitoids had been reported as biological control agents such as *Trichogramma* species [24].

In **Tunisia**, few experiments for biological control of *T. absoluta*, using the egg parasitoid wasp *T. cacoeciae*, were carried out [145]. In order to investigate the possible use of parasitoids to control *T. absoluta*, a survey of native *Trichogramma* species was conducted in oases of the South West of Tunisia and the locally collected strains of *T. bourarachae* were found promising biocontrol agents [73]. Also, a research was conducted to assess whether generalist indigenous parasitoids are adapting to *T. absoluta* in four Tunisian tomato-growing areas. Two ectoparasitoid species, *Bracon* sp. and *N. artynes*, had been found attacking and developing on *T. absoluta* while no egg and pupal parasitoids were found [232]. Very recently, Abbes et al. [234] assessed whether generalist indigenous parasitoids are adapting to *T. absoluta*, as an exotic host in Tunisian tomato crops. Their results showed that two ectoparasitoid species were found attacking and developing on *T. absoluta*: *Bracon* sp. and *Necremnus* sp. nr *artynes*, whereas no egg or pupal parasitoids were found.

In **Algeria**, the parasitoids *N. artynes*, *Neochrysocharis* sp., *Sympiesis* sp., *D. isaea* and *N. artynes* were found the most frequent and most abundant on *T. absoluta* [230]. Although the larval ectoparasitoid *D. phthorimaeae* was described as a parasitoid on *T. absoluta* in Algeria [258], Guenaoui et al. [15] never found it in their samples associated with this pest. In South-east Algeria, recent research explored the possibilities of the native antagonists (*N. artynes*, *Stenomiesius* sp., *N. formosa* and *B. hebetor*) for controlling *T. absoluta* [14]. In North-west Algeria, the list of the native enemies monitoring *T. absoluta* infestation in greenhouses was expanded to reach over 10 native species with three dominant eulophid species: *N. artynes*, *Stenomiesius* sp. and *N. formosa* [15].

In **Jordan**, Al-Jboory et al. [300] carried out a study in order to survey the natural enemies associated with *T. absoluta* and recorded the parasitic wasp *B. (H.) concolorans* for the first time. In **Egypt**, three different species of the egg parasitoids *Trichogramma* had been evaluated for controlling *T. absoluta* in greenhouses in Fayoum Governorate. *T. evanescens* was not strongly effective on tomato plants but possibility to be used in an IPM program against this pest [391]. Control methods for *T. absoluta* were carried in Baltiem district, Kafrel-Sheikh Governorate. *T. evanescens* was found important in combination with some other biocontrol agents [392]. In Kassala State, **Sudan**, a survey was conducted and revealed four effective parasitoids associated with *T. absoluta*: *B. (H.) concolorans*, *B. (H.) hebetor*, *E. cadenati* and *N. formosa* [19]. In **Saudi Arabia**, the invasive species *T. absoluta* was recorded for the first time in August 2010. The strategy for the management of this pest comprises different components among which is the egg parasitoid, *T. achaeae* [110]. In **Iran**, Farrokhi et al. [393] reported that the egg parasitoids *Trichogramma* spp. and larval parasitoid *Necremnus* sp. contribute to control of *T. absoluta*.

4.2. South American countries.

In South America, reports of multiple species of egg parasitoids, belonging to the families Encyrtidae [394, 395], Eupelmidae [396] and Trichogrammatidae [395] are available in the literature. The possible use of *Trichogramma* species as biological control agents of *T. absoluta* is currently considered in South America [38, 111] and Latin America [88]. In addition, the parasitoid *P. dignus* was reported as a major enemy of *T. absoluta* in tomato crops in South American countries [320, 322]. However, the biocontrol of *T. absoluta* by egg-, larval-, larval/pupal- and pupal-parasitoids in some important tomato-producing countries can be reviewed herein in some detail.

In **Brazil**, the biological control of *T. absoluta* by different species of *Trichogramma* was documented [63, 87, 88, 397, 398]. Some authors [85, 398, 399] pointed out that the actual success with *T. pretiosum* had been the result of rigorous agent selection. The biological aspects and the parasitism of six strains of this egg parasitoid, reared on eggs of *T. absoluta*, were studied in order to select those with best biological features and more aggressive to control

the pest [83, 400]. A recent study was carried out to select the most suitable *T. pretiosum* strain for the biological control of *T. absoluta* in tomato crops [92]. The *T. absoluta* eggs as host of another *Trichogramma* species, *T. evanescens*, were evaluated aiming to use this indigenous species for biological control of this pest [126]. In addition to *Trichogramma* spp., some of the abundant other parasitoids were *B. lucileae*, *Diadegma* sp., *Haltichella* sp., *Conura* sp. and *Diadegma* sp. [198, 302, 313, 314, 337].

In **Argentina**, evaluation of native larval parasitoids as BC agents against *Tuta absoluta* was carried out [401]. The biological control of *T. absoluta* using different species of *Trichogramma* was reported [402, 184, 403]. Inundative releases of *T. bactrae* on grown tomatoes, infested with *T. absoluta*, in greenhouses gave good control [170-172]. On the other hand, another trichogrammatid egg parasitoid, *T. nerudai*, is currently under evaluation for *T. absoluta* control [403]. In addition to Trichogrammatidae, several parasitoids have been reported on *T. absoluta*, with *P. dingus* and *D. phthorimaeae* as the most commonly found in commercial tomato crops [301, 323, 325]. Biology of *P. dingus* was extensively studied [320, 322, 323]. Its inoculative releases had been tested in greenhouses before *T. absoluta* reaches high population levels [321]. For the larval stage of *T. absoluta*, *P. dingus* could be considered as biocontrol agents against *T. absoluta* by means of augmentative releases (for details, see [260, 323, 403]). In connection with *D. phthorimaea*, a positive trait worth mentioning is its apparent specificity for *T. absoluta* [259, 395]. Although *N. formosa* was reported as potentially important parasitoid of *T. absoluta* in Argentina [267], Luna et al. [260] believed that they provided the first record of *N. formosa* parasitizing larvae of *T. absoluta* only in organic outdoor and protected tomato crops in Northern Buenos Aires Province. Recently, evaluation of different food sources to improve the larval ectoparasitoid *D. phthorimaeae* fitness had been carried out [404].

In **Chile**, the biological control of *T. absoluta* using different species of *Trichogramma* was investigated [405, 406]. *T. minutum* was collected for use against *T. absoluta* [160]. *T. pretiosum* was introduced from some South American countries into Chile and released for controlling *T. absoluta* in different tomato production regions [394, 407]. Two other parasitoids had been reported to cause considerable mortality in *T. absoluta* larvae, *Retisympiesis phthorimaea* [408] and *D. phthorimaeae* [409]. In **Colombia**, biological control of *T. absoluta* using different species of the egg parasitoids *Trichogramma* was documented [410]. *T. exiguum* has potential for use in integrated control programmes on tomatoes and thus at least 50% of routine insecticide applications are unnecessary [98]. Its parasitism levels reached 9.8-28.6% in open-field tomato [411]. A broad complex of larval parasitoids had been reported of which *A. gelechiidivoris* had received a particular attention [316, 318, 410]. Experiences of implementation of the parasitoid *A. gelechiidivoris* in greenhouses in Colombia had been conducted [412]. Unfortunately, Tachinidae had not been considered as promising biocontrol agents against *T. absoluta* [396, 413]. In Peru, as early as 1965, *T. minutum* was collected for use against *T. absoluta* while in 1973 *T. pintoi* was shipped to the same country for control of this pest [414]. As part of classical biological control schemes against *T. absoluta* in **Paraguay**, *T. pretiosum* had been moved extensively from some South American countries [415].

4.3. Parasitic mites against *T. absoluta*.

Some species of Pyemotidae mites (Acari: Actinedida) may be considered a new alternative for the biological control of *T. absoluta*. However, the detection of parasitic mites, particularly *P. ventricosus*, on this pest in a mass rearing kept at the Integrated Pest Management Laboratory (Federal University of Viçosa, Brazil) in October 2001 was narrated [384, 386]. The mite *P. tritici* was recorded attacking *T. absoluta* in some South American countries [384, 386, 416] as well as some *Pyemotes* spp. had been recorded on *T. absoluta* in some Mediterranean countries [2, 39]. The caterpillars and adults of this pest were quickly paralyzed by the mite venom. *Pyemotes* sp. can be a new alternative for the biological control of *T. absoluta*. However, this possibility must be better understood before it could be recommended, because *Pyemotes* sp. could also cause dermatitis in the humans [384].

5. PARASITIDS OF *T. absoluta*: PARASITISM MECHANISMS AND FACTORS AFFECTING THEIR PARASITIC EFFICIENCY.

All species of *Bracon*, as idiobiont ectoparasitoids paralyze the host larva at oviposition and the host does not develop any further while the parasitoid larva feeds from the outside [300]. As an idiobiont species, also, the larval solitary ectoparasitoid *D. phthorimaeae* halts the host development after attacking it by the injection of venom. One of the positive traits is its apparent specificity for *T. absoluta*. Among the mechanisms described for the parasitic behavior of this parasitoid, punctures with the ovipositor and mouthparts and the construction of a feeding tube were mentioned [395]. As reported by some authors [257, 259, 417], *D. phthorimaeae* practices non-concurrent destructive host feeding, that is, the adult female consumes host haemolymph and tissues without ovipositing, causing the death of the host.

With regard to factors affecting the parasitic efficiency of *T. absoluta* parasitoids, most efficient natural enemies have to show a high attack rate and be able to find their host whatever its density high or low. As for example, the functional response of *P. dingus* was described in laboratory. Females detect and parasitize the host within a wide

range of densities [322]. Considering the egg parasitoids *Trichogramma* species in inundative releases, one of the factors influencing on their parasitic efficiencies is the distribution pattern within the crop and host plant [418], and if there is a preference for specific niches they must coincide with those of the host [419]. Faria et al. [88] conducted a study to determine how *T. pretiosum* exploit the egg distribution of *T. absoluta* on the plant canopy, and the effect of plant morphology on parasitism in Brazil. The levels of *T. absoluta* oviposition and parasitism by *T. pretiosum* were higher on the upper third of the plant, decreasing downward along the plant canopy. In addition, the 2-tridecanone (2-TD) content in the tomato genotype has influence on the parasitism of *T. absoluta* eggs by *T. pretiosum* [84]. The parasitism efficiency of the egg parasitoid *T. achaeae* depends upon the use of high quantities of parasitoids/release, the infestation level by *T. absoluta*, and upon the presence of other natural enemies on the crop [420].

6. INTERFERENCE OR INTERACTION BETWEEN PARASITOIDS OF *T. absoluta* AND SOME OTHER NATURAL ENEMIES.

Taking into consideration the successful use of parasitoids as biocontrol agents for *T. absoluta*, it should be of great importance to investigate their interference, integration or competitiveness with some other biocontrol agents. Better understanding of these relationships among available natural enemies will facilitate optimal decisions on what to use and when to use them. Several works reported the promise of parasitoid/predator combination, under the laboratory or greenhouse conditions. Release of the egg parasitoid *T. achaeae* against *T. absoluta* appears to be particularly promising when used in combination with mirid predators [2, 103]. In the Mediterranean region of Turkey, some of the recommended control measures of *T. absoluta* involve integration of the egg parasitoids, especially *T. pretiosum* and *T. achaeae*, with the mirid predators, *Nesidiocoris tenuis* and *Macrolophus caliginosus* [240]. Almost similar results had been obtained for releasing of *T. evanescens* with *N. tenuis* together to decrease the numbers of *T. absoluta* eggs and larvae [39]. Desneux et al. [2, 421] carried out a choice experiment and suggested the importance of integrating the mirid predator *Macrolophus pygmaeus* with the oophagous parasitoid *T. achaeae* for inundative biological control of *T. absoluta* in the greenhouse tomato crop. An alternative release method for *N. tenuis* in combination with the parasitoid *N. artynes* reduced the control costs of *T. absoluta* [112]. To control *T. absoluta* in the South-East of France, Trottin-Caudal et al. [114] studied the use of *M. pygmaeus* and *T. achaeae*, alone and in combination. The best results were obtained when the two beneficials were released in combination. Recently, Chailleux et al. [117, 422] provided some contributions in the same aspect and recommended the combination use of *T. achaeae* with *M. pygmaeus* for effective control of *T. absoluta* under laboratory and greenhouse conditions.

Considering the integration of *T. pretiosum* with *Bacillus thuringiensis* applications in the greenhouse tomato in Brazil, this strategy had been proven as technically viable and economically efficient [423] instead of 87% parasitism of *T. absoluta* by *T. pretiosum* alone [398]. *B. thuringiensis* and the *T. absoluta*-egg parasite *T. achaeae* can provide good control of *T. absoluta* in tomato greenhouses [2, 36]. Furthermore, *B. thuringiensis* and *T. achaeae* have been shown to be effective against *T. absoluta* and could be a supplement to the mirid predator *N. tenuis* [112]. The interference or competitiveness between parasitoids of *T. absoluta* and each other has attracted the attention of few biological control researchers, especially in Argentina. The parasitoid *N. formosa* was found coexisting in most sites with the native parasitoid *D. phthorimaeae* in Northern Buenos Aires Province. When *N. formosa* was found at early season, the proportion of parasitism was much higher (92%) than that of *D. phthorimaeae*, but closer to equal rates (46%) in late crops. *N. formosa* could develop earlier during the cropping cycle because of its competitors, *D. phthorimaeae*, apparently finds better habitat conditions in late non-protected crops [259, 260]. Recently, some aspects of competence between the parasitoids *P. dingus* and *D. phthorimaeae* had been elucidated in the laboratory. The younger *D. phthorimaeae* females avoided to attack *T. absoluta* larvae previously parasitized by its competitor; meanwhile older ones could not help using parasitized hosts, and consequently succeeding over the endoparasitoid [325]. Moreover, non-indigenous *Trichogramma* strains or species used in biocontrol strategies may compete with native *Trichogramma*. When developing a biological control program using *Trichogramma* wasps, preference should always be given to indigenous species already present in the same region [67, 73]. In fact, a successful establishment of non-native species is theoretically related to their higher competitiveness compared to native species as well as to the reduced control by natural enemies. However, several research works on the conservation of indigenous parasitoids of *T. absoluta* will be discussed thereafter in the present review.

7. SIDE-EFFECTS OF SYNTHETIC AND BOTANICAL PESTICIDES ON PARASITOIDS OF *T. absoluta*.

As pointed out by several authors [27, 295, 424-427], the occurrence of *T. absoluta* at increasing population levels led growers to extensively use insecticides. These chemicals could cause many side-effects on natural enemies in tomato crops. Side-effects of some insecticides were evaluated in the laboratory to maximize compatibility of chemical and biological control methods. This will help minimize any negative impact on the natural enemies [428-430]. The available literature contains a huge number of papers on the assessment of side-effects of different

pesticides, synthetic or botanical, on various species of insect parasitoids. Several worldwide efforts have been reviewed herein aiming to increasingly attract the attention of entomologists and research institutions for selective and safer pesticides in respect to the parasitoids of *T. absoluta*.

Side-effects of some insecticides, chemically synthetic or of plant origin, had been tested on several species of Trichogrammid egg parasitoids. Effects of several insecticides were verified on the immature stages of *T. pretiosum*. Phenthoate and cartap were harmful, lambda-cyhalothrin was intermediate, tebufenozid and teflubenzuron were harmless to slightly harmful, respectively [431]. The side-effects of other insecticides were investigated on different developmental stages of the same egg parasitoid [432]. Botanically, the bioactivities of *Trichilia pallida* and *Azadirachta indica* (neem) extracts were evaluated on the same parasitoid [86]. In Egypt, effects of Chlorpyrifos (Dursban), Fenvalerate (Sumicidin) and Carbosulfan (Marshal) were studied on the pre-imaginal stages of *T. cacoeciae* [433]. Regarding the side-effects of some botanicals on the same parasitoid, two formulated products of each of Azadirachtin and Quassin had been tested. The residues of Quassin formulations were harmless [434]. The biological aspects and parasitism viability of *T. evanescens* stages were studied after treatment with herbicides (Glyphosate, Bromoxynil, Thiobencarb and Clodinafop-propargyl) [435]. Recently, toxicities of seven classes of chemicals were investigated against the same parasitoid. Neonicotinoids, pyrethroids and IGRs were less hazardous [436]. The side-effects of deltamethrin [437] and lambda-cyhalothrin, as well as a fungicide (basic copper sulphate) [438] were evaluated on *T. cordubensis*. The effects of lambda-cyhalothrin, cypermethrin, thiodicarb, profenophos, methoxyfenozide, and tebufenozide were investigated on *T. exiguum* [96]. For *Trichogramma platneri*, oxamyl and imidacloprid caused 100% mortality 48 hours after spraying but selectivity of diflubenzuron, fenoxycarb and tebufenozide was recorded for this egg parasitoid [439]. The side-effects of the carbamic pesticide cartap and some products of plant origin were evaluated on adults and immatures of *T. pintoii* in Peru [155, 326]. The residual effect of triflumuron and chlorfenapyr was evaluated on *T. bactrae* in Argentina [440].

Side-effects of insecticides, chemically synthetic or of plant origin, had been studied on parasitoids other than Trichogrammatidae. Adults of the parasitic microwasps *C. koehleri* and *D. gelechiidivoris* seemed to be sensitive to the carbamic pesticide cartap in Peru [326]. The acute toxicity and sublethal effect of Azadirachtin and borax salt plus citrus essential oil had been assessed on the larval ectoparasitoid *B. nigricans* [295]. Moreover, the risks of 14 pesticides, commonly used in tomato crops, caused multiple sublethal effects, notably reductions in parasitism rate on *T. absoluta*, fertility, longevity and also a male-biased sex-ratio of the progeny [388]. An extended laboratory bioassay was conducted to evaluate the toxicity and the duration of harmful activity of some modern insecticides on the parasitoid *Chelonus inanitus* in greenhouse [441].

8. CONSERVATION OF INDIGENOUS NATURAL PARASITOIDS

It is worth pointing out that conservation biological control (CBC) strategies that imply on the use of indigenous biological control agents could play a key role against invasive pests [442, 443]. It is the practice of enhancing the efficacy of natural enemies' assemblages that already exist in the area through modification of the environment, such as biodiversity conservation, landscape aesthetics, provision of clean water, reduce soil water retention or soil erosion [444], or of existing pesticide practices [445, 446]. In spite to this importance, CBC has long been a rather neglected form of biological control, but research in this field has increased markedly during the last decade [447-449]. Recent scientific reviews have considered CBC as a component of habitat manipulation [447, 450] or have focused on a part of CBC, e.g., plant-provided food for natural enemies (For several considerations, see [451-454]).

With regard to successful use of the parasitoid *N. formosa*, as well as other parasitoid species, against *T. absoluta*, biological studies on them would establish a foundation for a CBC programs [260]. Surveys were carried out in Catalonia (Spain) to study the native parasitoids of larvae (*N. arynes* and *H. zilahisebessi*) and eggs (*Trichogramma* sp.) of *T. absoluta*. Results available until now show that the conservation of native natural enemies may be one of the best strategies to achieve good control of this invasive pest [228]. Zappala et al. [38] identified the parasitoid complex of *T. absoluta* in Southern Italy and their survey highlighted that conservation of indigenous natural enemies, also by means of habitat management techniques, should be taken seriously into account when planning integrated management strategy of the tomato borer in the Mediterranean area. Because the natural enemies are able to learn [47], their response to their host can be improved when they are reared sequential generations on a host [47]. This occurs *via* enhancing their skills in orientation, host finding, host detection and acceptance [455].

9. CONCLUSIONS

In **conclusion**, parasitoids are a very important component of the natural enemy complex of *T. absoluta* and have been the most common type of natural enemies introduced for biological control of it. In this respect, several considerations should be kept in mind because the efficient parasitoids must show a high attack rate and be able to find their host, whatever its density high or low. The successful use of these parasitoids needs a good understanding of their biological characteristics, ecological requirements and characteristics of the agro-ecosystem. Also, it should

be of great importance to investigate their interference, integration or competitiveness with some other biocontrol agents. The competitiveness between parasitoids of *T. absoluta* and each other, of native and non-native species, must be studied. Because parasitoids are able to learn, their skills in orientation, host finding, host detection and acceptance can be enhanced. Selective pesticides that can be successfully used to control *T. absoluta* without adverse side-effects on its parasitoids are highly required. Better understanding of these relationships among available parasitoids will facilitate optimal decisions on what to use and when to use them.

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