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REVIEW

Releasing natural enemies and applying microbial and botanical pesticides for managing *Tuta absoluta* in the MENA region

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Abstract *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is a key insect pest, seriously damaging tomato crops and inducing tremendous yield and economic losses. The area of origin of this insect is in South America, while it has recently become an invasive pest in Europe, Africa, Asia and Central America. In the Middle East and North Africa (MENA) region, there has been growing evidence that biological control through field releases of egg parasitoids and predatory mirids generally induces promising control results of *T. absoluta* whenever the natural enemy species as well as the timing and release rates are suitably chosen. As such, application of botanical and/or microbial pesticides represent a potential control approach to be adopted against *T. absoluta*. This would decrease the detrimental side effects on non-target beneficial arthropods typically exhibited by hazardous chemical insecticide applications. The scientific literature emphasizing the (i) releases of parasitoids and/or predators, (ii) applications of biopesticides, and (iii) combination « release of parasitoid and/or predator + biopesticide treatments and/or other biorational tools», as sustainable control options of *T. absoluta* throughout the MENA region over the last decade, is comprehensively reviewed and unraveled herein.

Keywords South American tomato pinworm · Parasitoid · Predator · Biopesticide · Middle East · North Africa

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Introduction

Successfully established invasive organisms, such as insect pests, have often been proven to severely damage host crops and adversely influence ecosystem components and functioning as well as biodiversity dynamics, and to inducing substantial economic losses in the invaded areas (Sala et al., 2000; Pimentel et al. 2005; Olson 2006; Simberloff et al. 2013; Asplen et al. 2016; Kirichenko et al. 2019; McLaughlin and Dearden 2019; Milosavljević et al. 2019; Moore et al. 2019). Within this category of (exotic) invasive species, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is a devastating insect pest of tomato crops (*Solanum lycopersicon* L.) and a great economic challenge both in South America, its area of origin, and in several invaded areas of Europe, Africa, Asia and Central America (Campos et al. 2017; Biondi et al. 2018; Han et al. 2019; Mansour et al. 2018; Santana et al. 2019; Verheggen and Fontus 2019).

In addition to tomato, many cultivated and wild plant species belonging to the Solanaceae have also been reported as potential hosts for this pest (Desneux et al., 2010, 2011; Bawin et al. 2016; Sylla et al. 2019). *Tuta absoluta* has a high reproduction rate and may develop several generations per year in tomatoes (Desneux et al. 2010; Cocco et al. 2015; Biondi et al. 2018). However, successful establishment and rapid spread, as well as development and life cycle of this pest, depend on various factors, such as favorable temperature and relative humidity conditions, intensive tomato production system, and continuous host plant availability (Desneux et al. 2010, 2011; Cuthbertson et al. 2013; Machekano et al. 2018; Cherif et al. 2019a, b). Damage caused by *T. absoluta* larvae can be seen on tomato leaves, stems, twigs and fruits, which generally induce major crop yield and economic losses (Desneux et al. 2010; Campos et al. 2017; Biondi et al. 2018).

Considering these serious crop health and economic issues, several pest management approaches have been tested and, whenever possible, implemented against this pest worldwide (Biondi and Desneux 2019). These approaches include (i) prophylactic and cultural practices, (ii) pheromone-based tactics such as mass trapping and mating disruption; (iii) biological control releasing parasitoids and/or mirid predators, and (iv) application of insecticides, which constitutes the most commonly adopted control option (Desneux et al. 2010; Caparros-Megido et al. 2013; Cocco et al. 2013; Campos et al. 2017; Biondi et al. 2018; Majidiani et al. 2019; Mansour et al. 2019). The latter, when using broad-spectrum chemical pesticides, has generally two major constraints: adverse side effects on non-target beneficial arthropods including pest's natural enemies (parasitoids and predators) and pollinators (Mommaerts et al. 2006; Desneux et al. 2007; Arnó and Gabarra 2011; Wanumen et al. 2016; Biondi et al. 2018; Mansour et al. 2018) and development of insect resistance to various pesticide active substances used (Campos et al. 2014; Haddi et al. 2017; Roditakis et al. 2018; Guedes et al. 2019; Silva et al. 2019; Richardson et al. 2020). For these reasons, adopting ecofriendly control methods, as alternatives to widespread applications or even to misuse of hazardous chemical pesticides, is of crucial importance. In this regard, biological control programs through releases of either egg and/or larval parasitoids, mirid predators, or their combination, and applying biopesticides (microbial or botanical active substances) have successfully been incorporated in integrated pest management (IPM) programs against *T. absoluta* in South America, Europe, Africa, and Asia (Desneux et al. 2010; Zappalà et al. 2013; Han et al. 2019; Mansour et al. 2018; Ferracini et al. 2019).

Herein, all relevant, up-to-date published research focusing on testing, developing, implementing and enhancing various biorational control options against the invasive *T. absoluta* in the Middle East and North Africa (MENA) region, performed during the last decade, are thoroughly reviewed and elucidated for the first time.

The collection of scientific articles published in either English, French, or Arabic to be analyzed in the present article was achieved through searches on the online databases CAB Abstracts, Google Scholar, Web of Science, Scopus, and PubMed, using the following keywords in various combinations: "South American tomato pinworm", "Tomato leafminer", "*Tuta absoluta*", "biological control", "biorational control", "natural enemies", "egg parasitoid", "larval parasitoid", "*Trichogramma*", "release rate", "predatory mirids", "*Nesidiocoris*", "*Macrolophus*", "Entomopathogen", "microbial pesticide", "*Bacillus thuringiensis*", "spinosad", "fungus", "virus", "essential oils", "plant extracts", "botanical pesticide", "azadirachtin", "pheromone-mass trapping", "North Africa", "Middle East", "Mediterranean basin", "Asia", "tomato greenhouse", and "open-field tomato crops".

Releasing parasitoids, predators or their combination

Biological control using insect predators and parasitoids has long been regarded as an environmentally sound, effective and sustainable invasive pest management approach adopted as alternative to repetitive and extensive applications of harmful synthetic chemical pesticides (Barratt et al. 2018; Rossi Stacconi et al. 2018; Van Lenteren et al. 2018a; Giorgini et al. 2019; Konopka et al. 2019). Such a reality is particularly true and has been of great interest when developing the most suitable management programs of *T. absoluta* in several, but not all, invaded tomato-producing areas around the world (Cabello et al. 2009; Desneux et al. 2010; Biondi et al. 2018; Mansour et al. 2018; Ferracini et al. 2019; Salas Gervassio et al. 2019). More specifically, in the MENA region, biological control of *T. absoluta* exploiting pest's species-specific or generalist natural enemies has mainly been based on either consecutive single or combined augmentative releases of egg parasitoids and/or predatory bugs (Table 1). On the other hand, the performance of further different biocontrol categories such as conservation or classical biological control, which have been adopted in South America as well as

Table 1 Overview on parasitoid and/or predatory species successfully released alone or in combination against *Tuta absoluta* in open-field or greenhouses in countries of the MENA region

Parasitoid or predatory species released alone or in combination	Country	Reference
Trichogramma cacoeciae Marchal	Tunisia	Zouba and Mahjoubi (2010); Zouba et al. (2013); Cherif et al. (2019a, b; Mansour et al. (2019)
Trichogramma bourarachae Pintureau & Babault	Tunisia	Zouba et al. (2013)
Trichogramma achaeae Nagaraja & Nagarkatti	Saudi Arabia, Egypt	Hajjar (2012); El-Arnaouty et al. (2014); Kortam et al. (2014)
Trichogramma evanescens (Westwood)	Egypt, Turkey	Rizk (2016); Keçeci and Öztop (2017); Abdel-Razek et al. (2019)
Trichogramma euproctidis (Girault)	Egypt	El-Arnaouty et al. (2014)
Nesidiocoris tenuis (Reuter)	Morocco, Tunisia, Turkey, Israel, Iran	Elaini (2011); Ouardi et al. (2012); Shaltiel-Harpaz et al. (2016); Keçeci and Öztop (2017); Ettaib et al. (2019); Mirhosseini et al. (2019)
Macrolophus caliginosus Wagner	Egypt, Iran	Baniameri and Cheraghian (2012); Kortam et al. (2014)
Combination « *T. evanescens* + *N. tenuis* »	Turkey	Öztemiz (2013); Keçeci and Öztop (2017)
Combination « *Nabis pseudoferus* (Remane) + *Trichogramma brassicae* (Bezdenko)»	Iran	Mohammadpour et al. (2019)

in some European invaded areas, are yet to be tested and evaluated by researchers in North African and Middle Eastern countries.

Releases of parasitoids

In North Africa, field releases using *Trichogramma* egg parasitoids as a potential component of pest management have mainly been tested and developed in two countries: Tunisia and Egypt. In greenhouse tomatoes in southwestern Tunisia, a release rate of 40 *Trichogramma cacoeciae* Marchal (Hymenoptera: Trichogrammatidae) adults per plant significantly reduced *T. absoluta* crop damage by 75% (Zouba and Mahjoubi 2010). Similarly, releasing a total of 25,000 individuals of either indigenous parasitoid *T. cacoeciae* or *Trichogramma bourarachae* Pintureau & Babault per greenhouse (480 m^2 with a density of 3 plants per m^2) per week in southwestern Tunisia resulted in a reduction of either 78% or 87% in *T. absoluta* mines on tomato leaves, respectively (Zouba et al. 2013). In northern Egyptian tomato greenhouses, El-Arnaouty et al. (2014) demonstrated that releases of either parasitoid *Trichogramma euproctidis* (Girault) or *Trichogramma achaeae* Nagaraja & Nagarkatti (50 or 75 parasitoids per m^2) resulted in significant decrease of *T. absoluta* mines in greenhouses. However, in greenhouse tomato crops located in the same region in Egypt, releases of *T. achaeae* at a rate of 50 adults/m² significantly decreased number of *T. absoluta* larvae and mines on tomatoes (Kortam et al. 2014). As such, two releases of *Trichogramma evanescens* (Westwood) (about 190,000 parasitoids per ha) at seedling stage significantly reduced tomato leaf and fruit damage in Egyptian open-field conditions (Rizk 2016). In protected and open-field tomato crops of the Cap-Bon region, the largest tomato-producing area in Tunisia, Cherif et al. (2019a, b) provided evidence that three weekly releases of 20 *T. cacoeciae* adult parasitoids per plant significantly reduced pest's life stage densities and infestation rates caused by *T. absoluta*, implying that *T. cacoeciae* could be a promising biocontrol candidate of *T. absoluta* in conditions of northeastern Tunisia. More recently, field releases of *T. evanescens* at a rate of 1,500 parasitized eggs per card decreased the number of *T. absoluta* eggs on tomatoes under plastic tunnels in Giza governorate, northern Egypt (Abdel-Razek et al. 2019).

In some Asian Middle Eastern countries, mainly Turkey and Iran, egg parasitoids have been released alone or in combination with either predators (see the sub-Sect. 2.3) or other biorational tools (see the Sect. 5). In tomato greenhouses in western Turkey, twelve (seven in autumn and five in spring) releases of 75 *T. evanescens* parasitoids/m^2, repeated twice per week, were not sufficient to generate promising control results of egg and larval densities of *T. absoluta* on tomatoes (Keçeci and Öztop 2017).

In contrast to egg parasitoids that have been commercially released in tomato-producing areas in the MENA region and resulted in promising pest control, releases of larval parasitoids have not been sufficiently tested and developed as a powerful control tactic of *T. absoluta* in this geographical area. In all other concerned areas around the world, including South America and Europe, releases of larval and pupal parasitoids are not yet recommended as an effective control approach to control *T. absoluta* in tomato-producing areas where releasing egg parasitoids has been shown to be the most successful biological control approach (Calvo et al. 2016; Bodino et al. 2019; Ferracini et al. 2019).

Releases of predators

Releasing *Nesidiocoris tenuis* (Reuter) (Hemiptera: Miridae) has been a promising IPM option adopted against *T. absoluta* in Moroccan greenhouses where one or two releases of this predatory mirid at a rate of 1.5–2 individuals per m^2 are generally recommended after plantation (Elaini 2011; Ouardi et al. 2012). *Macrolophus caliginosus* Wagner (Hemiptera: Miridae) released respecting a density of 1–2 per m^2 after planting is among the IPM tools suggested for controlling *T. absoluta* in Iran (Baniameri and Cheraghian 2012). Likewise, releases of the predator *M. caliginosus* at a rate of 1–2 adult(s) per m² induced significant reduction in number of *T. absoluta* larvae and mines on tomato leaves in northern Egyptian greenhouses (Kortam et al. 2014). Either *N. tenuis* preplant augmentation with one egg per tomato seedling or augmentative release of commercially reared *N. tenuis* with one adult per plant released one month after planting was as effective as application of conventional insecticides, reducing *T. absoluta* densities and preventing crop damage in open-field tomatoes in Israel (Shaltiel-Harpaz et al. 2016). One release of *N. tenuis* at a rate of 2 adults per m^2 significantly reduced *T. absoluta* egg and larval densities infesting fruits in greenhouse tomato crops in western Turkey (Keçeci and Öztop 2017). Moreover, releasing the mirid bug *N. tenuis* before establishment of *T. absoluta* was shown to be more effective in enhancing overall tomato yield than releasing it after pest establishment in Iranian plastic greenhouse tomato crops (Mirhosseini et al. 2019). Lately, releases of an indigenous strain of *N. tenuis* at 2 adults per m^2 geothermal greenhouse in Kebili (South-West Tunisia) was by far more effective in eliminating all life stages of *T. absoluta* population, than an introcuded strain of this predatory species (Ettaib et al. 2019). This finding clearly indicates that, to effectively controlling *T. absoluta*, it would be more practical and promising to release native strain of the predator *N. tenuis* that are already well adapted to the specific abiotic conditions of geothermal greenhouses in southern Tunisia.

Similarly to the MENA region, in South America and Europe, some predators, mainly including the mirid bugs *N. tenuis*, *Macrolophus pygmaeus* (Rambur), and *M. basicornis* (Stål), have been released in greenhouse and/or open-field tomatoes and showed promising performance in controlling *T. absoluta* populations (Michaelides et al. 2018; Van Lenteren et al. 2018b; Ferracini et al. 2019). However, it is worth mentioning that despite the proven effectiveness of *N. tenuis* in controlling *T. absoluta* populations, previous studies provided evidence that this predatory mirid can also be considered as an insect pest seriously damaging host tomato crops (Arnó et al. 2010; Pérez-Hedo and Urbaneja 2016; Siscaro et al. 2019), implying that more attention should be paid to the possible phytophagous behavior of this predator before releasing it in tomatoes. In this context, *N. tenuis* phytophagy mitigation strategies, such as the use of tolerant varieties (Siscaro et al. 2019), of alternative food (e.g. tomato plants with sugar dispensers for attracting the damaging predatory nymphs) and/or plants including, for example, *Dittrichia viscosa* L. (Asteraceae) and *Sesamum indicum* (L.) (Pedaliaceae) (Biondi et al. 2016; Urbaneja-Bernat et al. 2019), have yet to be implemented in the MENA region to further reduce damage caused mainly by nymphs of this zoophytophagous mirid.

Combined releases of parasitoids and predators

Combined « parasitoid + predator » releases in the MENA region were mainly tested in Asian Middle Eastern countries including Turkey and Iran.

In greenhouses in the Mediterranean region in Turkey, numbers of *T. absoluta* eggs and larvae were significantly lower in plots with the combination « parasitoid *T. evanescens* + predatory bug *N. tenuis* », which significantly enhanced crop yield, relative to plots with releases of either natural enemy alone (Öztemiz 2013).

Similarly, thirteen combined releases of the parasitoid *T. evanescens* and the predatory mirid *N. tenuis* were proven to significantly reduce *T. absoluta* population densities and fruit infestation in greenhouse tomatoes in the western Mediterranean region of Turkey (Keçeci and Öztop 2017). In some circumstances, this category of combined releases would not generate success in controlling *T. absoluta*. For example, combined releases of the mirid bug *N. tenuis* with the egg parasitoid *Trichogramma brassicae* (Bezdenko) (Hymenoptera: Trichogrammatidae) were not sufficiently effective against *T. absoluta*, as compared with single releases of the predator *N. tenuis* before pest establishment that significantly decreased damage and enhanced tomato yield in plastic greenhouse conditions in Iran (Mirhosseini et al. 2019). In fact, intraguild predation or competition (Cabello et al. 2012, 2015; Perdikis et al. 2014), which is a particular case of behavioral interaction (interference) between either a parasitoid and a predator or even two predators, may occur and could hamper the overall effectiveness of the released natural enemy (Chailleux et al. 2013; Naselli et al. 2017). In this context, Mohammadpour et al. (2019) provided evidence that the increasing age of *T. absoluta* eggs parasitized by *T. brassicae* decreased the intensity of intraguild predation between the predatory bug *Nabis pseudoferus* (Remane) (Hemiptera: Nabidae) and the parasitoid *T. brassicae.* Accordingly, these authors suggested the integration of both natural enemies in biological control programs of *T. absoluta* in tomatoes in Iran, respecting the condition that the first release of this predator should be carried out about three days after the parasitoid (*T. brassicae*) release, preventing the predator from consuming *T. absoluta* parasitized eggs.

Application of botanical insecticides

Botanical pesticides based on plant essential oils, characterized by repellent, insecticidal, and growth-reducing effects on a wide range of crop pests, but also showing constraints (i.e. flammability, phytotoxicity, poor water solubility) affecting their effective use, have long been considered among the most effective and environmentally safe pest control tools, applied as sustainable alternative to broad-spectrum synthetic pesticides (Campolo et al. 2017, 2018, 2020; Benelli et al. 2019a, b; Giunti et al. 2019; Petrović et al. 2019; Soares et al. 2019; Isman 2020). Application of biopesticide active substances to cope with problems caused by insect pests has been gaining increasing importance over the two last decades, which has also been consistent for refining IPM programs against the invasive *T. absoluta* in several countries including, among others, those of the MENA region (Table 2).

In greenhouse conditions of Kafr El-Sheikh (northern Egypt), treatments based on either *Artemisia cina* Berg & Schmidt extract (500 ppm) or clove oil (500 ppm) extracted from *Syzigium aromaticum* (L.) were effective in reducing *T. absoluta* larvae and mines. Consequently, these natural active substances could be suggested as possible potential ecofriendly control tools of *T. absoluta* in Egypt (Derbalah et al. 2012). Similarly, clove oil (*S. aromaticum*) applied at 0.1 $\mu L\ L^{-1}$ significantly reduced numbers of insect larvae and overall infestation rates of tomatoes by *T. absoluta* in semi-field conditions, implying that this natural active substance can be used to control this pest as a sustainable alternative to the application of traditional chemical pesticides in Egypt (Ebadah et al. 2016). In the same context, laboratory bioassays showed that essential oil of *S. aromaticum* buds caused 100% mortality of *T. absoluta* larvae, thereby it has been proposed as suitable biopesticide to control this pest in Morocco (Benchouikh et al. 2016). High mortality rates of *T. absoluta* second instar larvae were obtained in laboratory conditions, following application of either plant extract grown in South-West Morocco (Souss region): leaves of *Thymus vulgaris* L. causing 97% mortality or seeds of *Ricinus communis* L. inducing 80% mortality (Ait Taadaouit et al. 2012). Increased doses of essential oils extracted from peels of *Citrus aurantium* L. significantly increased mortality percentage of *T. absoluta* third instar larvae; thereby applying such natural active substances as botanical insecticide could enhance *T. absoluta* management programs in greenhouse tomatoes in Tunisia (Zarrad et al. 2013). Moreover, under field conditions in Minia Governorate (Upper Egypt), foliar application of either garlic extract (*Allium sativum* L.) at 5 $mL\ L^{-1}$, lemon grass extract (*Cymbopogon citratus* Stapf) at 25 $gm\ L^{-1}$ or Basil (*Ocimum basilicum* L.) essential oil at 0.5% significantly reduced numbers of *T. absoluta* mines per plant and tomato foliar damage, which significantly improved the quality of fruit yield (Hussein et al. 2015). Laboratory bioassays showed that azadirachtin applied at 1 $mL\ L^{-1}$ generated promising efficacy against *T. absoluta* larvae inside tomato leaf mines, causing 92% insect mortality, hence

Table 2 Effective botanical insecticides tested, recommended or implemented alone in integrated pest management programs against *Tuta absoluta* in the MENA region

Botanical pesticide active substances	Country	Reference
Azadirachtin (or neem or *Azadirachta indica* A. Juss)	Egypt, Lebanon, Turkey, Iran	Baniameri and Cheraghian (2012); Birgücü et al. (2014); Abd El-Ghany et al. (2016); El Hajj et al. (2017); Abdel-Ghany et al. (2018)
Clove oil (or *Syzigium aromaticum* (L.) essential oils)	Egypt, Morocco	Derbalah et al. (2012); Benchouikh et al. (2016); Ebadah et al. (2016)
Artemisia cina Berg & Schmidt extracts	Egypt	Derbalah et al. (2012)
Citrus aurantium L. peel essential oils	Tunisia	Zarrad et al. (2013)
Lemon grass (*Cymbopogon citratus* Stapf) extracts	Egypt	Hussein et al. (2015)
Garlic (*Allium sativum* L.) extracts	Egypt	Hussein et al. (2015)
Ricinus communis L. extracts	Morocco	Ait Taadaouit et al. (2012)
Basil (*Ocimum basilicum* L.) essential oils	Egypt	Hussein et al. (2015)
Rosemary (*Rosmarinus officinalis* L.) essential oils	Egypt	Sammour et al. (2018)
Thyme (*Thymus vulgaris* L.) essential oils	Morocco, Egypt	Ait Taadaouit et al. (2012); Sammour et al. (2018)
Melia azedarach L. extracts	Syria, Lebanon	Ibrahim et al. (2011); Hammad et al. (2019)
Jojoba seed extracts (Simmondsin)	Saudi Arabia	Abdel-Baky and Al-Soqeer (2017)
Cardamom (*Elettaria cardamomum* (Maton)) seed essential oils	Iran	Chegini and Abbasipour (2017)
Ajwain (*Carum copticum* L.) essential oils	Iran	Piri et al. (2020)

farmers are encouraged to use this botanical insecticide in IPM programs against *T. absoluta* in Egypt (Abd El-Ghany et al. 2016). More recently, field experiments in Bani Sweif Governorate (Upper Egypt) spraying infested tomatoes with either rosemary oil (*Rosmarinus officinalis* L.) or thyme oil (*T. vulgaris*) reduced *T. absoluta* larval populations by more than 80%. Consequently, these plant extract active substances could be applied for controlling *T. absoluta* in Egypt as alternative to treatments with conventional chemical pesticides (Sammour et al. 2018). In the same country, the botanical extract azadirachtin applied 5 mL L^{-1} ha^{-1} showed 70–83% reduction in *T. absoluta* larval densities and improved crop yield in greenhouse conditions in northern Egypt (Abdel-Ghany et al. 2018).

In addition to North African countries of the MENA region, plant extracts acting as insecticides have also been tested and, whenever appropriate, implemented in Asian tomato-producing areas of this region. Field application of *Melia azedarach* L. plant extracts at 3 mL L^{-1} in Homs region (Syria) resulted in 84.48% efficacy on *T. absoluta* larvae in tomatoes (Ibrahim et al. 2011). Likewise, aqueous extracts of indigenous *M. azedarach* applied as a powder formulation caused significant decrease of eggs, larvae, pupae and newly emerging *T. absoluta* moths under laboratory conditions. Therefore, this botanical formulation could be recommended to be used, at field rate of 2/3 kg in 1,000 ppm per 1,500 L ha^{-1} in consecutive applications on plants infested with *T. absoluta* in Lebanon (Hammad et al. 2019). Applying azadirachtin, registered as an emulsifiable concentrate or wettable powder, every week after detection of infestation and < 10 moths per pheromone trap per week is an IPM tactic proposed to control *T. absoluta* in Iran (Baniameri and Cheraghian 2012). As such, azadirachtin applied at 3 g L^{-1} reduced numbers of first instar larvae by 70–86% under laboratory conditions (Jallow et al. 2018). Simmondsin extracted from jojoba seeds by acetone and water signifcantly reduced *T. absoluta* second instar larvae in laboratory conditions, and accordingly they could be integrated in programs for controlling *T. absoluta* in organic farming in Saudi Arabia (Abdel-Baky and Al-Soqeer 2017). Besides, seed essential oils extracted from cardamom

(*Elettaria cardamomum* (L.)) and applied at 3 (outside leaf) or 10 (inside leaf) μL L^{-1} of air exhibited high toxicity potential against second instar larvae of *T. absoluta*; therefore they could be used in sustainable management of this pest in Iranian greenhouse tomato crops (Chegini and Abbasipour 2017). Applying NeemAzal® (azadirachtin) at 3 mL L^{-1} in a 15-day frequency proved to be an effective biorational control option against *T. absoluta* in Lebanese tomato greenhouses where it induced significant reduction in numbers of mines on leaves, larvae and percent of damaged fruits (El Hajj et al. 2017). Lately, based on laboratory bioassays, Piri et al. (2020) demonstrated that application of Ajwain (*Carum copticum* L.) essential oil exhibited a significant poential in controlling fourth instar larvae of *T. absoluta*, which might constitute a future promising biorational option to control this pest in Iran.

Application of microbial insecticides

Over the last decades, applying biopesticides that are issued from different microbials such as fungi, bacteria and viruses has been regarded as a powerful effective and environmentally sound control option against a wide range of insect pest species (Van Driesche et al. 2008; Chandler et al. 2011; Czaja et al. 2015; Arthurs and Dara 2019; De la Cruz Quiroz et al. 2019; Tahir et al. 2019) including the pinworm *T. absoluta* (Biondi et al. 2018). Overall, among several active organisms used, the most applied and successful microbial pesticide in the MENA region was that based on various *Bacillus thuringiensis* strains (Table 3).

Either microbial biopesticide *B. thuringiensis* applied at 4.5 g L^{-1} or spinosad, a product based on the soil actinomycete *Saccharopolyspora spinosa* (Metz and Yao), applied at 1 mL L^{-1} generated satisfactory control of *T. absoluta* larvae infesting leaves in greenhouse tomatoes of northeastern Tunisia (Grissa-Lebdi et al. 2011). However, in Tunisian semi-natural conditions, *B. thuringiensis* var. *kurstaki* applied at 2.5 g L^{-1} provided promising control performance (mortality > 70%) on first, second and third instar larvae of *T. absoluta* (Hafsi et al. 2012). Culture filtrate of *B. thuringiensis* (500 ppm) applied under northern Egyptian greenhouse conditions was effective against *T. absoluta* in tomatoes where it decreased numbers of larvae and mine blotches (Derbalah et al. 2012). Satisfactory efficacy against *T. absoluta* larvae was observed in tomato greenhouses in Esfahan (Iran) after application of *B. thuringiensis* var. *kurstaki* (Baniameri and Cheraghian 2012). The biosurfactant *Bacillus amyloliquefaciens* AG1, causing serious histological damages in the larval midgut of *T. absoluta* (Ben Kheder et al. 2015) and the vegetative insecticidal protein *B. thuringiensis* Vip3Aa16, inducing a microvillus damage and an epithelial cell rupture

Table 3 Effective microbial insecticides tested, recommended or implemented alone in integrated pest management programs against *Tuta absoluta* in the MENA region

Microbal pesticide active substances	Country	Reference
Bacillus thuringiensis (various strains)	Tunisia, Morocco, Algeria, Egypt, Lebanon, Saudi Arabia, Kuwait, Turkey, Iran	Grissa-Lebdi et al. (2011); Baniameri and Cheraghian (2012); Derbalah et al. (2012); Hafsi et al. (2012); Hajjar (2012); Ouardi et al. (2012); Birgücü et al. (2014); El-Aassar et al. (2015); Sellami et al. (2015); El Hajj et al. (2017); Abdel-Ghany et al. (2018); Jallow et al. (2018); Harizia et al. (2019)
Bacillus amyloliquefaciens AG1	Tunisia	Ben Kheder et al. (2015)
Spinosad	Tunisia, Egypt, Turkey, Iran	Baniameri and Cheraghian (2012); Braham et al. (2012); Dağlı et al. (2012); Hanafy and El-Sayed (2013); Birgücü et al. (2014); El-Aassar et al. (2015); Soliman (2015); Abd El-Ghany et al. (2016, 2018)
Beauveria bassiana	Egypt, Tunisia	Abdel-Raheem et al. (2015); Abd El-Ghany et al. (2016) ; Borgi et al. (2016)
Metarhizium anisopliae	Egypt	Abdel-Raheem et al. (2015) ; El-Aassar et al. (2015)
Verticillium lecanii	Tunisia, Egypt	Braham et al. 2012; Abdel-Raheem et al. (2015)
Phthorimaea operculella granulovirus	Tunisia	Ben Tiba et al. (2019)

in *T. absoluta* third instar larva midguts, cessation of feeding, body retraction, overall paralysis, and death of several larvae (Sellami et al. 2015) are further promising active substances that could be incorporated in IPM programs of *T. absoluta* in Tunisia. Applying *B. thuringiensis* or the entomophatogenic fungus *Metarhizium anisopliae* at 2 g L^{-1}, and spinosad at 0.75 mL L^{-1} provided promising control of *T. absoluta* larvae and reduced their damage in open-field tomatoes in Menoufia Governorate, northern Egypt (El-Aassar et al. 2015). As such, application of *B. thuringiensis* (1 g L^{-1}) at 10-day frequency generated promising results in limiting damage caused by *T. absoluta* larvae on leaves and fruits in tomato greenhouses in Lebanon (El Hajj et al. 2017). Lately, *B. thuringiensis* var. *kurstaki* at 0.5 g L^{-1} and *Beauveria bassiana* at 1.5 g L^{-1} induced 55–65% and 45.5–58.5% mortality of *T. absoluta* second instar larvae, respectively, based on laboratory bioassays (Jallow et al. 2018). A commercial formulation of *B. thuringiensis* var. *kurstaki* (IAB Bt), a bioinsecticide available as a wettable powder with a concentration of 32000 IU g^{-1}, and registered against some lepidopteran pests in Algeria showed a high efficacy in controlling *T. absoluta* larval stages (particularly the youngest ones) under laboratory conditions, when applied at either concentration 500, 650 or 800 ppm (Harizia et al. 2019).

According to Baniameri and Cheraghian (2012), applying the biopesticide spinosad at 200–250 mL ha^{-1} in the case of 10 moths (or more) caught per trap per week is a recommended control tool of *T. absoluta* in Iran. In greenhouse tomatoes of Center-East Tunisia, either microbial spinosad applied at 0.6 mL L^{-1} or commercial formulation of *Verticillium lecanii* (Biocatch®) applied at 1 mL L^{-1} was effective in controlling *T. absoluta* larvae (Braham et al. 2012). Laboratory bioassays showed that spinosad applied at its recommended dose in Turkey (120 mg L^{-1}) resulted in 100% larval mortality (Dağlı et al. 2012). Under open-field tomatoes in Kalyobiya Governorate (northern Egypt), spinosad applied at either 238 or 285 mL ha^{-1} for controlling *T. absoluta* was more effective in decreasing infestations on tomato leaves than some chemical insecticides such as pyridalyl, indoxcarb, chlorantraniliprole and chlorfenapyr (Hanafy and El-Sayed 2013). Based on field studies in Sharkia governorate (northern Egypt), spinosad sprayed every 10 days during two months at 0.2 mL L^{-1} was effective in controlling *T. absoluta* larvae on leaves, which consequently reduced the percentage of infested tomato fruits (Soliman 2015).

Laboratory experiments demonstrated that either entomopathogenic fungus *B. bassiana*, *M. anisopliae* or *V. lecanii* applied at 107 conidia mL^{-1} was effective against one or more life stage(s) of *T. absoluta*: *B. bassiana* and *M. anisopliae* being effective on both eggs and first instar larvae, whereas *V. lecanii* was effective on first and third instar larvae (Abdel-Raheem et al. 2015). Such findings would be useful for incorporating pesticide treatments based on these microbials in IPM programs of *T. absoluta* in Egypt. As such, either microbial active substance spinosad (0.6 or 0.3 mL L^{-1}) or *B. bassiana* (5×10^5 spore per m^2) exhibited outstanding efficacy against *T. absoluta* larvae inside and outside tomato treated leaf mines, thereby applying these substances could be an effective biorational tool for farmers for managing *T. absoluta* in Egypt (Abd El-Ghany et al. 2016). Laboratory experiments showed that a spontaneous mutant of a local strain of *B. bassiana* was very effective against *T. absoluta* larval populations, which could be a strong basis for developing of a bioinsecticide to control controlling *T. absoluta* in Tunisia (Borgi et al. 2016). Moreover, Ben Tiba et al. (2019) provided evidence that, under laboratory conditions, a local isolate of *Phthorimaea operculella* granulovirus (PhopGV Tu1.11) exhibited potential toxicity on *T. absoluta* larvae, which could be developed and incorporated as a biopesticide active substance in IPM programs against *T. absoluta* in Tunisia. Spinosad sprayed at 0.3 mL L^{-1} ha^{-1} and *B. thuringiensis* var. *kurstaki* applied at 2 g L^{-1} ha^{-1} were proven to be the most effective microbial pesticides, causing respectively 78–97% and 78–91% reduction in *T. absoluta* larval population and enhancing crop yield, as compared to either entomopathogenic fungus *M. anisopliae* at 5 mL L^{-1} ha^{-1} or *B. bassiana* at 5 mL L^{-1} ha^{-1}), causing 46–75% reduction in larval densities in northern Egyptian greenhouses (Abdel-Ghany et al. 2018).

Although some microbial-based pesticides proved to be effective against *T. absoluta*, previous research studies provided evidence that the application of some active substances could exert some serious constraints. Indeed, spinosad for example was shown to present adverse lethal effects on adults and pupae of the ectoparasitoid *Bracon nigricans* Szépligeti (Hymenoptera: Braconidae), and sublethal effects on the predators *Orius laevigatus* Fieber (Hemiptera: Antocoridae) and *M. pygmaeus* (Hemiptera: Miridae), in contrast to the harmless *B. thuringiensis* (Biondi et al. 2012, 2013;

Ricupero et al. 2020), as well as on the egg parasitoid *T. brassicae* (Parsaeyan et al. 2020). Additionally, spinosad can show high resistance in its target *T. absoluta* populations (Campos et al. 2014), which could result in control failure, compromising pest management objectives.

Different combinations of biorational control tools

In addition to combining releases of parasitoids with predators, other categories of combinations were also tested against *T. absoluta* before to be implemented in IPM programs throughout the MENA region. These combinations include (i) « natural enemy release + botanical pesticide », (ii) « natural enemy release + microbial pesticide », (ii) natural enemy release + entomophatogenic nematode », (iv) « natural enemy release + pheromone-based mass trapping », and (v) « microbial pesticide + botanical pesticide » (Table 4).

Releasing 25 *T. achaeae* adult parasitoids per m² in combination with release of the predatory mirid *M. caliginosus* at 1–4 adult(s) per m² and application of the microbial pesticide *B. thuringiensis* at 1 g L^{-1} resulted in notable reduction in *T. absoluta* larvae and mines on tomato plants in northern Egyptian greenhouse conditions (Kortam et al. 2014). In other cases, applying the microbial insecticide *B. thuringiensis* in combination with releasing the egg parasitoid *T. evanescens* and pheromone mass trapping generated significant decrease in *T. absoluta* larval densities and crop damage in northern Egyptian (Kafrel-Sheikh Governorate) open-field tomatoes (Khidr et al. 2013). Likewise, four releases of *T. evanescens* parasitoids at about 190,000 ha^{-1} combined with bioinsecticide (Protecto and Spinosad bait) applications against *T. absoluta* induced a significant reduction in leaf and fruit damages in Egyptian open-field tomatoes (Rizk 2016).

In Iranian greenhouse tomato crops, releases of either egg parasitoid *Trichogramma embryophagum* (Hartig) (Hymenoptera: Trichogrammatidae) or *T. brassicae* in combination with applying *B. thuringiensis* significantly reduced *T. absoluta* larval densities and leaf mines (Alsaedi et al. 2017). As such, releases of *T. brassicae* in combination with spinosad treatment, or the biopesticide combination "spinosad + *B. thuringiensis*" significantly decreased both *T. absoluta* densities and related leaf mines on tomato crops in Iranian greenhouse conditions (Jamshidnia et al. 2018). On the other hand, in commercial tomato plastic greenhouses in northern Egypt, Adly and Nouh (2019) showed that the combined use of the parasitoid *T. euproctidis* (weekly releases of 50 parasitoids per m^2) and the entomopathogenic nematode *Heterorhabditis bacteriophora* strain HP88 decreased density of *T. absoluta* larvae gradually until the end of the season, and accordingly they recommended this combination to be integrated as a main component of pest management against *T. absoluta* in Egyptian greenhouse tomato crops. Moreover, biweekly releases of *Trichogrammatoidea bactrae* Nagaraja (Hymenoptera: Trichogrammatidae) (143,000 and 238,000 parasitoids ha^{-1}) in combination with pheromone-mass trapping significantly reduced infestation levels and resulted in higher yield rates in open-field tomato crops in Egypt (Goda et al. 2015). In this context, Ahmadi and Poorjavad (2018) showed that neither *T. evanescens* nor *T. brassicae* prarasitoids (1,000 released individuals for each species) were caught in sticky delta traps baited with *T. absoluta* sex pheromone in greenhouses in Iran, which apparently indicate a possible compatibility between both pest control tools whenever applied in combination. Based on laboratory experiments, it was proven that using the combination « predator *N. pseudoferus* + entomopathogenic fungus *M. anisopliae* » could show promise in pest management programs of *T. absoluta* in Iran, however experiments in field (natural) conditions are needed to confirm these preliminary laboratory findings (Alikhani et al. 2019).

Regarding combinations involving microbial and botanical insecticides, field studies in Iran demonstrated that using of *B. thuringiensis* var. *kurstaki* in combination with the botanical active substance azadirachtin generated the highest long term effect on *T. absoluta* larval abundance as well as on induced leaf and fruit damage (with 100% reduction), as compared to applying each biopesticide alone (Nazarpour et al. 2016). Spraying the botanical neem Azal (3 mL L^{-1}) in combination with the microbial *B. thuringiensis* (1 g L^{-1}) significantly reduced *T. absoluta* larval populations as well as damage on leaves (mines) and fruits in Lebanese greenhouse tomatoes (El Hajj et al. 2017).

Likewise, in the absence of any releases of natual enemies, applying of the combination «azadirachtin (6.857 L ha^{-1}) + *B. thuringiensis* var. *kurstaki* (11.428 L ha^{-1})» showed potential control effect since it significantly reduced *T. absoluta* larval densities and improved healthy yield production in northern Egyptian open-field tomato crops (Khidr et al. 2013).

Table 4 Promising combinations of various biorational control tools tested, recommended or implemented in integrated pest management programs against *Tuta absoluta* in the MENA region

Different biorational control combinations	Country	Reference
Parasitoid *T. achaeae* + predator *M. caliginosus* + *B. thuringiensis*	Egypt	Kortam et al. (2014)
Parasitoid *T. evanescens* + *B. thuringiensis* + pheromone-mass trapping	Egypt	Khidr et al. (2013)
Parasitoid *T. evanescens* + spinosad	Egypt	Rizk (2016)
Parasitoid *Trichogramma embryophagum* (Hartig) + *B. thuringiensis*	Iran	Alsaedi et al. (2017)
Parasitoid *T. brassicae* + *B. thuringiensis*	Iran	Alsaedi et al. (2017)
Parasitoid *T. brassicae* + spinosad	Iran	Jamshidnia et al. (2018)
Parasitoid *T. euproctidis* + the entomopathogenic nematode *Heterorhabditis bacteriophora* strain HP88	Egypt	Adly and Nouh (2019)
Parasitoid *T. bactrae* + pheromone-mass trapping	Egypt	Goda et al. (2015)
Parasitoid *T. evanescens* + pheromone-mass trapping	Iran	Ahmadi and Poorjavad (2018)
Parasitoid *T. brassicae* + pheromone-mass trapping	Iran	Ahmadi and Poorjavad (2018)
Predator *N. pseudoferus* + *M. anisopliae*	Iran	Alikhani et al. (2019)
B. thuringiensis var. *kurstaki* + azadirachtin	Egypt, Iran	Khidr et al. (2013); Nazarpour et al. (2016)
Botanical neem Azal + *B. thuringiensis*	Lebanon	El Hajj et al. (2017)
Azadirachtin + *B. thuringiensis*	Turkey, Kuwait	Birgücü et al. (2014); Jallow et al. (2018)
Azadirachtin + *B. bassiana*	Kuwait	Jallow et al. (2018)
Spinosad + *B. thuringiensis*	Iran	Jamshidnia et al. (2018)

In commercial polycarbonate greenhouses in Waffra (southern Kuwait), either combination « azadirachtin (3 g L^{-1}) + *B. thuringiensis* (0.5 g L^{-1}) » or « azadirachtin (3 g L^{-1}) + *B. bassiana* (1.5 g L^{-1}) » induced significant decrease in *T. absoluta* larval mines on leaves and significantly reduced the number of damaged fruits, thereby improved tomato crop yield. These findings represent a strong indication that such microbial-based combinations could be sucessfully incorporated in IPM programs against *T. absoluta* in greenhouses tomatoes in Kuwait as well as in other Middle Eastern countries (Jallow et al. 2018).

Conclusion and future directions

Since its first detection in 2008 in the MENA region, more specifically in North Africa, and its further spread to Middle Eastern Asian countries, farmers have been facing serious tomato crop health problems coupled with substantial annual economic losses posed by the destructive pest *T. absoluta*. In an attempt to effectively manage this new threat to tomato industry, various control tools were tested, and whenever possible implemented in IPM programs, in different MENA countries located either in northern Africa or south-western Asia. In general, IPM programs against *T. absoluta* in the MENA region have been relied heavily on applying effective but hazardous synthetic chemical pesticides that could exert adverse side effects on beneficial arthropods, coupled with the pest's high potential for developing insect resistance to a number of chemical substances. However, fortunately, in the few last years, it has become evident due to growing awareness linked to these alarming realities, that using biorational approaches as alternative to the the injudicious use of such synthetic pesticides is of foremost importance for ensuring sustainable management of this pest. Among biorational tactics considered as alternative to hazardous chemicals, biological control using egg and/or larval parasitoids has always been considered as sustainable component of IPM programs against *T. absoluta* in the MENA region. Importantly, it is necessary to know which are the parasitoid species that have great potential in reducing *T. absoluta* densities in tomatoes, in which conditions these species could be released, and which are the most recommended release rates of the species to be used for optimizing their field effectiveness. Additionally, notable advances in efforts focused on environmentally-sound management of *T. absoluta* based on either microbial or botanical (plant extract) pesticides have been at the forefront since the first report of the pest in the MENA region. In this context, different control scenarios have been adopted alone or combined with other ecofriendly options (natural enemy release and/or pheromone-mass trapping), depending on the agro-ecosystem nature and conditions in each concerned tomato-producing region. However, in some cases, such biorational approaches might have serious weaknesses such as failures in controlling the pest or detrimental side effects on human health, environment and non-target beneficial organisms. Accordingly, special attention should be paid to such possible serious constraints when developing and implementing IPM programs against this pest in the MENA region, and it is necessary to remain as vigilant as possible regarding this issue. Ideally, the performance of further novel biorational options should be carefully and thoroughly investigated by scientists belonging to the MENA region in the near future, in strong collaboration with farmers as well as with decision-making and policy-maker professionals.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

Abd El-Ghany, N. M., Abdel-Razek, A. S., Ebadah, I. M. A., & Mahmoud, Y. A. (2016). Evaluation of some microbial agents, natural and chemical compounds for controlling tomato leaf miner, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). *Journal of Plant Protection Research, 56*, 372–379.

Abd El-Ghany, N. M., Abdel-Razek, A. S., Djelouah, K., & Moussa, A. (2018). Efficacy of bio-rational insecticides against *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) on tomatoes. *Bioscience Research, 15*, 28–40.

Abdel-Baky, N. F., & Al-Soqeer, A. A. (2017). Controlling the 2nd instar larvae of *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) by simmondsin extracted from jojoba seeds in KSA. *Journal of Entomology, 14*, 73–80.

Abdel-Raheem, M. A., Ismail, I. A., Abdel-Rahman, R. S., Abdel-Rhman, I. E., & Reyad, N. F. (2015). Efficacy of three entomopathogenic fungi on tomato leaf miner, *Tuta absoluta* in tomato crop in Egypt. *Swift Journal of Agricultural Research, 1*, 15–21.

Abdel-Razek, A. S., Masry, S. H. D., Sadek, H. E., & Gaafar, N. M. (2019). Efficacy of *Trichogramma* wasps for controlling tomato leaf miner *Tuta absoluta*. *Archives of Phytopathology and Plant Protection, 52*, 443–457.

Adly, D., & Nouh, G. M. (2019). Impact of combine releases of the egg parasitoid, *Trichogramma euproctidis* (Girault) and the entomopathogenic nematode, *Heterorhabditis bacteriophora* to control *Tuta absoluta* (Meyrick) in tomato greenhouses in Egypt. *Egyptian Journal of Biological Pest Control, 29*, 91.

Ahmadi, S., & Poorjavad, N. (2018). Behavioral and biological effects of exposure to *Tuta absoluta* (Lepidoptera: Gelechiidae) sex pheromone on several *Trichogramma* (Hymenoptera: Trichogrammatidae) populations. *Journal of Economic Entomology, 111*, 2667–2675.

Ait Taadaouit, N., Hsaine, M., Rochdi, A., Nilahyane, A., & Bouharroud, R. (2012). Effet des extraits végétaux méthanoliques de certaines plantes marocaines sur *Tuta absoluta* (Lepidoptera, Gelechiidae). *EPPO Bulletin, 42*, 275–280.

Alikhani, M., Safavi, S. A., & Iranipour, S. (2019). Predation response of *Nabis pseudoferus* (Hemiptera: Nabidae) on untreated and *Metarhizium anisopliae*-treated larvae of *Tuta absoluta* (Lepidoptera: Gelechidae). *Journal of Crop Protection, 8*, 311–322.

Alsaedi, G., Ashouri, A., & Talaei-Hassanloui, R. (2017). Assessment of two *Trichogramma* species with *Bacillus thuringiensis* var. *krustaki* for the control of the tomato leafminer *Tuta absoluta* in Iran. *Open Journal of Ecology, 7*, 112–124.

Arnó, J., & Gabarra, R. (2011). Side effects of selected insecticides on the *Tuta absoluta* (Lepidoptera: Gelechiidae) predators *Macrolophus pygmaeus* and *Nesidiocoris tenuis* (Hemiptera: Miridae). *Journal of Pest Science, 84*, 513–552.

Arnó, J., Castane, C., Riudavets, J., & Gabarra, R. (2010). Risk of damage to tomato crops by the generalist zoophytophagous predator *Nesidiocoris tenuis* (Reuter) (Hemiptera: Miridae). *Bulletin of Entomological Research, 100*, 105–115.

Arthurs, S., & Dara, S. K. (2019). Microbial biopesticides for invertebrate pests and their markets in the United States. *Journal of Invertebrate Pathology, 165*, 13–21.

Asplen, M. K., Anfora, G., Biondi, A., Choi, D. S., Chu, D., Daane, K. M., et al. (2016). Invasion biology of spotted wing Drosophila (*Drosophila suzukii*): a global perspective and future priorities. *Journal of Pest Science, 88*, 469–494.

Baniameri, V., & Cheraghian, A. (2012). The first report and control strategies of *Tuta absoluta* in Iran. *EPPO Bulletin, 42*, 322–324.

Barratt, B. I. P., Moran, V. C., Bigler, F., & van Lenteren, J. C. (2018). The status of biological control and recommendations for improving uptake for the future. *BioControl, 63*, 155–167.

Bawin, T., Dujeu, D., De Backer, L., Francis, F., & Verheggen, F. J. (2016). Ability of *Tuta absoluta* (Lepidoptera: Gelechiidae) to develop on alternative host plant species. *The Canadian Entomologist, 148*, 434–442.

Ben Kheder, S., Boukedi, H., Kilani-Feki, O., Chaib, I., Laarif, A., Abdelkefi-Mesrati, L., & Tounsi, S. (2015). *Bacillus amyloliquefaciens* AG1 biosurfactant: Putative receptor diversity and histopathological effects on *Tuta absoluta* midgut. *Journal of Invertebrate Pathology, 132*, 42–47.

Ben Tiba, S., Larem, A., Laarif, A., Fritsch, E., Undorf-Spahn, K., et al. (2019). The potential of novel African isolates of

Phthorimaea operculella granulovirus for the control of *Tuta absoluta*. *Journal of Applied Entomology, 143*, 11–20.

Benchouikh, A., Allam, T., Kribii, A., & Ounine, K. (2016). The study of the insecticide effect of the essential oil of *Syzygium aromaticum* L. against larvae of *Tuta absoluta*. *International Journal of Innovation and Scientific Research, 20*, 188–194.

Benelli, G., Pavela, R., Cianfaglione, K., Nagy, D. U., Canale, A., & Maggi, F. (2019a). Evaluation of two invasive plant invaders in Europe (*Solidago canadensis* and *Solidago gigantea*) as possible sources of botanical insecticides. *Journal of Pest Science, 92*, 805–821.

Benelli, G., Pavel, R., Zorzetto, C., Sánchez-Mateo, C. C., Santini, G., Canale, A., & Maggi, F. (2019b). Insecticidal activity of the essential oil from *Schizogyne sericea* (Asteraceae) on four insect pests and two non-target species. *Entomologia Generalis, 39*, 9–18.

Biondi, A., & Desneux, N. (2019). Special issue on *Tuta absoluta*: recent advances in management methods against the background of an ongoing worldwide invasion. *Journal of Pest Science, 92*, 1313–1315.

Biondi, A., Desneux, N., Siscaro, G., & Zappalà, L. (2012). Using organic-certified rather than synthetic pesticides may not be safer for biological control agents: selectivity and side effects of 14 pesticides on the predator *Orius laevigatus*. *Chemosphere, 87*, 803–812.

Biondi, A., Zappalà, L., Stark, J. D., & Desneux, N. (2013). Do biopesticides affect the demographic traits of a parasitoid wasp and its biocontrol services through sublethal effects? *PloS One, 8*(9), e76548.

Biondi, A., Zappalà, L., Di Mauro, A., Tropea Garzia, G., Russo, A., Desneux, N., & Siscaro, G. (2016). Can alternative host plant and prey affect phytophagy and biological control by the zoophytophagous mirid *Nesidiocoris tenuis*? *BioControl, 61*, 79–90.

Biondi, A., Guedes, R. N. C., Wan, F. H., & Desneux, N. (2018). Ecology, worldwide spread and management of the invasive South American tomato pinworm, *Tuta absoluta*: Past, present and future. *Annual Review of Entomology, 63*, 239–258.

Birgücü, A. K., Bayindir, A., Çelikpençe, Y., & Karaca, I. (2014). Growth inhibitory effects of bio- and synthetic insecticides on *Tuta absoluta* (Meyrick, 1917) (Lepidoptera: Gelechiidae). *Türkiye Entomoloji Dergisi, 38*, 389–400.

Bodino, N., Ferracini, C., & Tavella, L. (2019). Functional response and age-specific foraging behaviour of *Necremnus tutae* and *N. cosmopterix*, native natural enemies of the invasive pest *Tuta absoluta* in Mediterranean area. *Journal of Pest Science, 92*, 1467–1478.

Borgi, I., Dupuy, J. W., Blibech, I., Lapaillerie, D., Lomenech, A. M., Rebai, A., Ksantini, M., Bonneu, M., & Gargouri, A. (2016). Hyper-proteolytic mutant of *Beauveria bassiana*, a new biological control agent against the tomato borer. *Agronomy for Sustainable Development, 36*, 60.

Braham, M., Glida-Gnidez, H., & Hajji, L. (2012). Management of the tomato borer, *Tuta absoluta* in Tunisia with novel insecticides and plant extracts. *EPPO Bulletin, 42*, 291–296.

Cabello, T., Gallego, J., Vila, E., Soler, A., Del Pino, M., Carnero, A., Hernandez-Suarez, E., & Polaszek, A. (2009). Biological control of the South American tomato pinworm, *Tuta absoluta* (Lep.: Gelechiidae), with releases of *Trichogramma achaeae* (Hym.: Trichogrammatidae) in tomato greenhouses of Spain. *IOBC/WPRS Bulletin, 492*, 25–230.

Cabello, T., Gallego, J. R., Fernandez, F. J., Gamez, M., Vila, E., Del Pino, M., & Hernandez–Suarez, E. (2012). Biological control strategies for the South American tomato moth (Lepidoptera: Gelechiidae) in greenhouse tomatoes. *Journal of Economic Entomology, 105*, 2085–2096.

Cabello, T., Bonfil, F., Gallego, J. R., Fernandez, F. J., Gamez, M., & Garay, J. (2015). Can interactions between an omnivorous hemipteran and an egg parasitoid limit the level of biological control for the tomato pinworm? *Environmental Entomology, 44*, 12–26.

Calvo, F. J., Soriano, J. D., Stansly, P. A., & Belda, J. E. (2016). Can the parasitoid *Necremnus tutae* (Hymenoptera: Eulophidae) improve existing biological control of the tomato leafminer *Tuta absoluta* (Lepidoptera: Gelechiidae)? *Bulletin of Entomological Research, 106*, 502–511.

Campolo, O., Cherif, A., Ricupero, M., Siscaro, G., Grissa-Lebdi, K., et al. (2017). Citrus peel essential oil nanoformulations to control the tomato borer, *Tuta absoluta*: chemical properties and biological activity. *Scientific Reports, 7*, 13036.

Campolo, O., Giunti, G., Russo, A., Palmeri, V., & Zappala, L. (2018). Essential oils in stored product insect pest control. *Journal of Food Quality, 2018*, 1–18.

Campolo, O., Puglisi, I., Barbagallo, R. N., Cherif, A., Ricupero, M., et al. (2020). Side effects of two citrus essential oil formulations on a generalist insect predator, plant and soil enzymatic activities. *Chemosphere, 257*, 127252.

Campos, M. R., Rodrigues, A. R. S., Silva, T. B. M., Silva, V. R. F., Guedes, R. N. C., Alvaro, H., & Siqueira, A. (2014). Spinosad and the tomato borer *Tuta absoluta*: A bioinsecticide, an invasive pest threat, and high insecticide resistance. *PLoS ONE, 9*, e103235.

Campos, M. R., Biondi, A., Adiga, A., Guedes, R. N. C., & Desneux, N. (2017). From the Western Palaearctic region to beyond: *Tuta absoluta* ten years after invading Europe. *Journal of Pest Science, 90*, 787–796.

Caparros-Megido, R., Haubruge, E., & Verheggen, F. J. (2013). Pheromone-based management strategies to control the tomato leafminer, *Tuta absoluta* (Lepidoptera: Gelechiidae). A review. *Biotechnology, Agronomy, Society and Environment, 17*, 475–482.

Chailleux, A., Bearez, P., Pizzol, J., Amiens-Desneux, E., Ramirez-Romero, R., & Desneux, N. (2013). Potential for combined use of parasitoids and generalist predators for biological control of the key invasive tomato pest *Tuta absoluta*. *Journal of Pest Science, 86*, 533–541.

Chandler, D., Bailey, A. S., Tatchell, G. M., Davidson, G., Greaves, J., & Grant, W. P. (2011). The development, regulation and use of biopesticides for integrated pest management. *Philosophical Transactions of the Royal Society B, 366*, 1987–1998.

Chegini, S. G., & Abbasipour, H. (2017). Chemical composition and insecticidal effects of the essential oil of cardamom, *Elettaria cardamomum* on the tomato leaf miner, *Tuta absoluta*. *Toxin Reviews, 36*, 12–17.

Cherif, A., Attia-Barhoumi, S., Mansour, R., Zappalà, L., & Grissa-Lebdi, K. (2019a). Elucidating key biological parameters of *Tuta absoluta* on different host plants and under various temperature and relative humidity regimes. *Entomologia Generalis, 39*, 1–7.

Cherif, A., Mansour, R., Barhoumi-Attia, S., Zappalà, L., & Grissa-Lebdi, K. (2019b). Effectiveness of different release rates of *Trichogramma cacoeciae* (Hymenoptera: Trichogrammatidae) against *Tuta absoluta* (Lepidoptera: Gelechiidae) in protected and open field tomato crops in Tunisia. *Biocontrol Science and Technology, 29*, 149–161.

Cocco, A., Deliperi, S., & Delrio, G. (2013). Control of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in greenhouse tomato crops using the mating disruption technique. *Journal of Applied Entomology, 137*, 16–28.

Cocco, A., Deliperi, S., Lentini, A., Mannu, R., & Delrio, G. (2015). Seasonal phenology of *Tuta absoluta* (Lepidoptera: Gelechiidae) in protected and open-field crops under Mediterranean climatic conditions. *Phytoparasitica, 43*, 713–724.

Cuthbertson, A. G. S., Mathers, J. J., Blackburn, L. F., Korycinska, A., Luo, W., Jacobson, R. J., & Northing, P. (2013). Population development of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) under simulated UK glasshouse conditions. *Insects, 4*, 185–197.

Czaja, K., Góralczyk, K., Struciński, P., Hernik, A., Korcz, W. et al. (2015). Biopesticides – towards increased consumer safety in the European Union. *Pest Management Science, 71*, 3–6.

Dağlı, F., İkten, C., Sert, E., & Bölücek, E. (2012). Susceptibility of tomato borer, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) populations from Turkey to 7 different insecticides in laboratory bioassay. *EPPO Bulletin, 42*, 305–311.

De la Cruz Quiroz, R., Maldonado, J. J. C., Alanis, M. D. J. R., Torres, J. A., & Saldívar, R. P. (2019). Fungi-based biopesticides: shelf-life preservation technologies used in commercial products. *Journal of Pest Science, 92*, 1003–1015.

Derbalah, A. S., Morsey, S. Z., & El-Samahy, M. (2012). Some recent approaches to control *Tuta absoluta* in tomato under greenhouse conditions. *African Entomology, 20*, 27–34.

Desneux, N., Decourtye, A., & Delpuech, J. M. (2007). The sublethal effects of pesticides on beneficial arthropods. *Annual Review of Entomology, 52*, 81–106.

Desneux, N., Wajnberg, E., Wyckhuys, K. A. G., Burgio, G., Arpaia, S., et al. (2010). Biological invasion of European tomato crops by *Tuta absoluta*: ecology, geographic expansion and prospects for biological control. *Journal of Pest Science, 83*, 197–215.

Desneux, N., Luna, M. G., Guillemaud, T., & Urbaneja, A. (2011). The invasive South American tomato pinworm, *Tuta absoluta*, continues to spread in Afro-Eurasia and beyond: the new threat to tomato world production. *Journal of Pest Science, 84*, 403–408.

Ebadah, I. M., Shalaby, S. E. M., & Moawad, S. S. (2016). Impact of certain natural plant oils and chemical insecticides against tomato insect pests. *Journal of Entomology, 13*, 84–90.

El Hajj, A. K., Rizk, H., Gharib, M., Houssein, M., Talej, V., Taha, N., Aleik, S., & Mousa, Z. (2017). Management of *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) using biopesticides on tomato crop under greenhouse conditions. *Journal of Agricultural Science, 9*, 123–129.

El-Aassar, M. R., Soliman, M. H. A., & Abd Elaal, A. A. (2015). Efficiency of sex pheromone traps and some bio and chemical insecticides against tomato borer larvae, *Tuta absoluta* (Meyrick) and estimate the damages of leaves and fruit tomato plant. *Annals of Agricultural Science, 60*, 153–156.

El-Arnaouty, S.A., Pizzol, J., Galal, H.H., Kortam, M.N., Afifi, A.I., Beyssat, V., Desneux, N., Biondi, A., & Heikal, I.H. (2014). Assessment of two *Trichogramma* species for the control of *Tuta absoluta* in North African tomato greenhouses. *African Entomology, 22*, 801–809.

Elaini, R. (2011). Les aspects pratiques de la lutte contre *Tuta absoluta*: Cas de la région du Souss (Maroc). Control Strategies: Integrated Pest Management (IPM). EPPO/IOBC/FAO/NEPPO. Joint International Symposium on management of *Tuta absoluta* (tomato borer, Lepidoptera: Gelechiidae), November 16–18, 2011, Agadir, Morocco, p. 44.

Ettaib, R., Aoun, F., Assadi, B., Ben Belgacem, A., Chouikhi, S., & BelKadhi, M. S. (2019). Comparison of strains of *Nesidiocoris tenuis* against *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) under geothermal greenhouses in southern Tunisia. *Journal of Oasis Agriculture and Sustainable Development, 1*, 23–26.

Ferracini, C., Bueno, V. H. P., Dindo, M. L., Ingegno, B. L., Luna, M. G., Gervassio, N. G. S., Sánchez, N. E., Siscaro, G., van Lenteren, J. C., Zappalà, L., & Tavella, L. (2019). Natural enemies of *Tuta absoluta* in the Mediterranean basin, Europe and South America. *Biocontrol Science and Technology, 29*, 578–609.

Giorgini, M., Wang, X. G., Wang, Y., Chen, F. S., Hougardy, E., et al. (2019). Exploration for native parasitoids of *Drosophila suzukii* in China reveals a diversity of parasitoid species and narrow host range of the dominant parasitoid. *Journal of Pest Science, 92*, 509–522.

Giunti, G., Palermo, D., Laudani, F., Algeri, G. M., Campolo, O., & Palmeri, V. (2019). Repellence and acute toxicity of a nano-emulsion of sweet orange essential oil toward two major stored grain insect pests. *Industrial Crops and Products, 142*, 111869.

Goda, N.F., El-Heneidy, A.H., Djelouah, K., & Hassan, N. (2015). Integratedpestmanagement of thetomatoleafminer, Tutaabsoluta (Meyrick) (Lepidoptera: Gelechiidae) in tomatofields in Egypt. *Egyptian Journal of Biological Pest Control, 25*, 655–661.

Grissa-Lebdi, K., Skander, M., Mhafdhi, M., & Belhadj, R. (2011). Lutte intégrée contre la mineuse de la tomate, Tuta absoluta Meyrick (Lepidoptera: Gelechiidae) en Tunisie. Entomologie Faunistique - Faunistic Entomology, 63, 125–132.

Guedes, R. N. C., Roditakis, E., Campos, M. R., Haddi, K., Bielza, P., Siqueira, H. A. A., Tsagkarakou, A., Vontas, J., & Nauen, R. (2019). Insecticide resistance in the tomato pinworm *Tuta absoluta*: patterns, spread, mechanisms, management and outlook. *Journal of Pest Science, 92*, 1329–1342.

Haddi, K., Berger, M., Bielza, P., Rapisarda, C., Williamson, M. S., Moores, G., & Bass, C. (2017). Mutation in the ace-1 gene of the tomato leaf miner (*Tuta absoluta*) associated with organophosphates resistance. *Journal of Applied Entomology, 141*, 612–619.

Hafsi, A., Abbes, K., Chermiti, B., & Nasraoui, B. (2012). Response of the tomato miner *Tuta absoluta* (Lepidoptera: Gelechiidae) to thirteen insecticides in semi-natural conditions in Tunisia. *EPPO Bulletin, 42*, 312–316.

Hajjar, M. J. (2012). IPM of *Tuta absoluta* in Alhasa, Saudi Arabia. Conference paper. Available at: https://www.

researchgate.net/publication/267525745 [accessed on June 24th 2020].

Hammad, E. A. F., Abbass, A., Abbass, M., Haidar, Z. M., El-Chemali, J., Jawdeh, A., Y., & Ibrahim, L. (2019). Bioactivity of indigenous *Melia azedarach* extracts against the tomato leafminer, *Tuta absoluta*. *Journal of Agricultural Science and Technology A, 9*, 8–25.

Han, P., Bayram, Y., Shaltiel-Harpaz, L., Sohrabi, F., Saji, A., et al. (2019). *Tuta absoluta* continues to disperse in Asia: Damage, ongoing management and future challenges. *Journal of Pest Science, 92*, 1317–1327.

Hanafy, H. E. M., & El-Sayed, W. (2013). Efficacy of bio-and chemical insecticides in the control of *Tuta absoluta* (Meyrick) and *Helicoverpa armigera* (Hübner) infesting tomato plants. *Australian Journal of Basic and Applied Science, 7*, 943–948.

Harizia, A., Benguerai, A., & Boukhari, Y. (2019). Larvicidal activity of *Bacillus thuringiensis kurstaki* against *Tuta absoluta* (Lepidoptera: Gelechiidae). *Lebanese Science Journal, 20*, 352–362.

Hussein, N. M., Hussein, M. I., Gadel Hak, S. H., Shaalan, H. S., & Hammad, M. A. (2015). Effect of two plant extracts and four aromatic oils on *Tuta absoluta* population and productivity of tomato cultivar Gold Stone. *Journal of Plant Protection and Pathology, Mansoura University, 6*, 969–985.

Ibrahim, M., Al-Jouri, E., Mehrez, E., Edrees, M., Aodie, B., & Al-Masrey, A. (2011). The primary record, seasonal activity and possibility of controlling tomato leafminer *Tuta absoluta* (Povolny) at Homs region – Syria (in Arabic). *Furat University Journal, 12*, 51–71.

Isman, M. B. (2020). Botanical insecticides in the twenty-first century - Fulfilling their promise? *Annual Review of Entomology, 65*, 233–249.

Jallow, M. F. A., Dahab, A. A., Albaho, M. S., & Devi, V. Y. (2018). Efficacy of some biorational insecticides against *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) under laboratory and greenhouse conditions in Kuwait. *Journal of Applied Entomology, 143*, 187–195.

Jamshidnia, A., Abdoli, S., Farrokhi, S., & Sadeghi, R. (2018). Efficiency of spinosad, Bacillus thuringiensis and Trichogramma brassicae against the tomato leafminer in greenhouse. BioControl, 63, 619–627.

Keçeci, M., & Özto, A. (2017). Possibilities for biological control of *Tuta absoluta* (Meyrick, 1917) (Lepidoptera: Gelechiidae) in the western Mediterranean Region of Turkey. *Türkiye Entomoloji Dergisi, 41*, 219–230.

Khidr, A. A., Gaffar, S. A., Nada, M. S., Taman, A. A., & Salem, F. A. (2013). New approach for controlling tomato leafminer, *Tuta absoluta* in tomato fields in Egypt. *Egyptian Journal of Agricultural Research, 91*, 335–348.

Kirichenko, N., Augustin, S., & Kenis, M. (2019). Invasive leafminers on woody plants: a global review of pathways, impact, and management. *Journal of Pest Science, 92*, 93–106.

Konopka, J. K., Gariepy, T. D., Haye, T., Zhang, J., Rubin, B. D., & McNeil, J. N. (2019). Exploitation of pentatomids by native egg parasitoids in the native and introduced ranges of *Halyomorpha halys*: a molecular approach using sentinel egg masses. *Journal of Pest Science, 92*, 609–619.

Kortam, M. N., El-Arnaouty, S. A., Afifi, A. I., & Heikal, I. H. (2014). Efficacy of different biological methods for controlling the tomato leaf miner, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) on tomato in greenhouse in Egypt. *Egyptian Journal of Biological Pest Control, 24*, 523–528.

Machekano, H., Mutamiswa, R., & Nyamukondiwa, C. (2018). Evidence of rapid spread and establishment of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in semiarid Botswana. *Agriculture and Food Security, 7*, 48.

Majidiani, S., PourAbad, R. F., Laudani, F., Campolo, O., Zappalà, L., Rahmani, S., et al. (2019). RNAi in *Tuta absoluta* management: effects of injection and root delivery of dsRNAs. *Journal of Pest Science, 92*, 1409–1419.

Mansour, R., Brévault, T., Chailleux, A., Cherif, A., Grissa-Lebdi, K., et al. (2018). Occurrence, biology, natural enemies and management of *Tuta absoluta* in Africa. *Entomologia Generalis, 38*, 83–112.

Mansour, R., Cherif, A., Attia-Barhoumi, S., Zappalà, L., & Grissa-Lebdi, K. (2019). *Tuta absoluta* in Tunisia: ten years of invasion and pest management. *Phytoparasitica, 47*, 461–474.

McLaughlin, G. M., & Dearden, P. K. (2019). Invasive insects: management methods explored. *Journal of Insect Science, 19*, 17.

Michaelides, G., Sfenthourakis, S., Pitsillou, M., & Seraphides, N. (2018). Functional response and multiple predator effects of two generalist predators preying on *Tuta absoluta* eggs. *Pest Management Science, 74*, 332–339.

Milosavljević, I., El-Shafie, H. A., Faleiro, J. R., Hoddle, C. D., Lewis, M., & Hoddle, M. S. (2019). Palmageddon: the wasting of ornamental palms by invasive palm weevils, *Rhynchophorus* spp. *Journal of Pest Science, 92*, 143–156.

Mirhosseini, M. A., Fathipour, Y., Soufbaf, M., & Reddy, G. V. P. (2019). Implications of using two natural enemies of *Tuta absoluta* (Lepidoptera: Gelechiidae) toward tomato yield enhancement. *Bulletin of Entomological Research, 109*, 617–625.

Mohammadpour, M., Hosseini, M., Karimi, J., & Hosseininaveh, V. (2019). Effect of age-dependent parasitism in eggs of *Tuta absoluta* (Lepidoptera: Gelechiidae) on intraguild predation between *Nabis pseudoferus* (Hemiptera: Nabidae) and *Trichogramma brassicae* (Hymenoptera: Trichogrammatidae). *Journal of Insect Science, 19*, 27.

Mommaerts, V., Sterk, G., & Smagghe, G. (2006). Hazards and uptake of chitin synthesis inhibitors in bumblebees Bombus terrestris. Pest Management Science, 62, 752–758.

Moore, L., Tirello, P., Scaccini, D., Toews, M. D., Duso, C., & Pozzebon, A. (2019). Characterizing damage potential of the brown marmorated stink bug in cherry orchards in Italy. *Entomologia Generalis, 3–4*, 271–283.

Naselli, M., Biondi, A., Tropea Garzia, G., Desneux, N., Russo, A., Siscaro, G., & Zappalà, L. (2017). Insights on food webs associated with the South American tomato pinworm. *Pest Management Science, 73*, 1352–1357.

Nazarpour, L., Yarahmadi, F., Saber, M., & Rajabpour, A. (2016). Short and long term effects of some bio-insecticides on *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) and its coexisting generalist predators in tomato fields. *Journal of Crop Protection, 5*, 331–342.

Olson, L. J. (2006). The economics of terrestrial invasive species: a review of the literature. *Agricultural and Resource Economics Review, 35*, 178–194.

Ouardi, K., Chouibani, M., Rahel, M. A., & Akel, E., M (2012). Stratégie nationale de lutte contre la mineuse de la tomate *Tuta absoluta* Meyrick. *EPPO Bulletin, 42*, 281–290.

Öztemiz, S. (2013). Population of *Tuta absoluta* and natural enemies after releasing on tomato grown greenhouse in Turkey. *African Journal of Biotechnology, 12*, 1882–1887.

Parsaeyan, E., Saber, M., Safavi, S. A., Poorjavad, N., & Biondi, A. (2020). Side effects of chlorantraniliprole, phosalone and spinosad on the egg parasitoid. *Trichogramma brassicae. Ecotoxicology, 29*, 1052–1061.

Perdikis, D., Lucas, E., Garantonakis, N., Giatropoulos, A., Kitsis, P., Maselou, D., Panagakis, S., Lampropoulos, P., Paraskevopoulos, A., Lykouressis, D., & Fantinou, A. (2014). Intraguild predation and sublethal interactions between two zoophytophagous mirids, *Macrolophus pygmaeus* and *Nesidiocoris tenuis*. *Biological Control, 70*, 35–41.

Pérez-Hedo, M., & Urbaneja, A. (2016). The zoophytophagous predator *Nesidiocoris tenuis*: A successful but controversial biocontrol agent in tomato crops. In A. Horowitz & I. Ishaaya (Eds.), *Advances in insect control and resistance management*. Cham: Springer. https://doi.org/10.1007/978-3-319-31800-4_7.

Petrović, M., Popović, A., Kojić, D., Šućur, J., et al. (2019). Assessment of toxicity and biochemical response of *Tenebrio molitor* and *Tribolium confusum* exposed to *Carum carvi* essential oil. *Entomologia Generalis, 38*, 333–348.

Pimentel, D., Zuniga, R., & Morrison, D. (2005). Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological Economics, 52*, 273–288.

Piri, A., Sahebzadeh, N., Zibaee, A., Sendi, J. J., Shamakhi, L., & Shahriari, M. (2020). Toxicity and physiological effects of ajwain (Carum copticum, Apiaceae) essential oil and its major constituents against *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). *Chemosphere, 256*, 127103.

Richardson, E. B., Troczka, B. J., Gutbrod, O., Davies, T. E., & Nauen, R. (2020). Diamide resistance: 10 years of lessons from lepidopteran pests. *Journal of Pest Science, 93*, 911–928.

Ricupero, M., Abbes, K., Haddi, K., Kurtulus, A., Desneux, N., et al. (2020). Combined thermal and insecticidal stresses on the generalist predator *Macrolophus pygmaeus*. *Science of the Total Environment*, 138922.

Rizk, A.M. (2016). Effectiveness of different bio-techniques for controlling the pinworm, Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae). Egyptian Journal of Biological Pest Control, 26, 797–802.

Roditakis, E., Vasakis, E., García-Vidal, L., del Rosario Martínez-Aguirre, M., Rison, J. L., Haxaire-Lutun, M. O., Nauen, R., Tsagkarakou, A., & Bielza, P. (2018). A four-year survey on insecticide resistance and likelihood of chemical control failure for tomato leaf miner *Tuta absoluta* in the European/ Asian region. *Journal of Pest Science, 91*, 421–435.

Rossi Stacconi, M. V., Amiresmaeili, N., Biondi, A., Carli, C., Caruso, S., et al. (2018). Biological control of the invasive spotted wing Drosophila trough augmentative releases of the cosmopolitan parasitoid *Trichopria drosophilae*. *Biological Control, 117*, 188–196.

Sala, O. E., Stuart Chapin, I. I. I., Armesto, S., Berlow, J. J., Bloomfield, E., J., et al (2000). Global biodiversity scenarios for the year 2100. *Science, 287*, 1770–1774.

Salas Gervassio, N. G., Aquino, D., Vallina, C., Biondi, A., & Luna, M. G. (2019). A re-examination of *Tuta absoluta* parasitoids in South America for optimized biological control. *Journal of Pest Science, 92*, 1343–1357.

Sammour, E. A., Kandil, M. A., Abdel-Aziz, N. F., Agamy, E. A. E. M., El-Bakry, A. M., & Abdelmaksoud, N. M. (2018). Field evaluation of new formulation types of essential oils against *Tuta absoluta* and their side effects on tomato plants. *Acta Scientific Agriculture, 2*, 15–22.

Santana, P. A., Kumar, L., Da Silva, R. S., & Picanço, M. C. (2019). Global geographic distribution of *Tuta absoluta* as affected by climate change. *Journal of Pest Science, 92*, 1373–1385.

Sellami, S., Cherif, M., Abdelkefi-Mesrati, L., Tounsi, S., & Jamoussi, K. (2015). Toxicity, activation process, and histopathological effect of *Bacillus thuringiensis* vegetative insecticidal protein Vip3 Aa16 on *Tuta absoluta*. *Applied Biochemistry and Biotechnology, 175*, 1992–1999.

Shaltiel-Harpaz, L., Gerling, D., Graph, S., Kedoshim, H., Azolay, L., Rozenberg, T., Nachache, Y., Steinberg, S., Allouche, A., & Alon, T. (2016). Control of the tomato leafminer, *Tuta absoluta* (Lepidoptera: Gelechiidae), in open-field tomatoes by indigenous natural enemies occurring in Israel. *Journal of Economic Entomology, 109*, 120–131.

Silva, J. E., Ribeiro, L. M. D. S., Vinasco, N., Guedes, R. N. C., & Siqueira, H.ÁA. (2019). Field-evolved resistance to chlorantraniliprole in the tomato pinworm *Tuta absoluta*: inheritance, cross-resistance profile, and metabolism. *Journal of Pest Science, 92*, 1421–1431.

Simberloff, D., Martin, J.-L., Genovesi, P., Maris, V., Wardle, D. A., Aronson, J., Courchamp, F., Galil, B., Garcia-Berthou, E., Pascal, M., Pyšek, P., Sousa, R., Tabacchi, E., & Vilà, M. (2013). Impacts of biological invasions: what's what and the way forward. *Trends in Ecology and Evolution, 28*, 58–66.

Siscaro, G., Lo Pumo, C., Tropea Garzia, G., Tortorici, S., Gugliuzzo, A., Ricupero, M., Biondi, A., & Zappalà, L. (2019). Temperature and tomato variety influence the development and the plant damage induced by the zoophytophagous mirid bug *Nesidiocoris tenuis*. *Journal of Pest Science, 92*, 1049–1056.

Soares, M. A., Campos, M. R., Passos, L. C., Carvalho, G. A., Haro, M. M., et al. (2019). Botanical insecticide and natural enemies: a potential combination for pest management against *Tuta absoluta*. *Journal of Pest Science, 92*, 1433–1443.

Soliman, M. H. A. E. (2015). Effect of two control tactics in the integrated pest management on the population of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelichiidae) in tomato fields. *Egyptian Academic Journal of Biological Sciences A. Entomology, 8*, 129–138.

Sylla, S., Brévault, T., Monticelli, L. S., Diarra, K., & Desneux, N. (2019). Geographic variation of host preference by the invasive tomato leaf miner *Tuta absoluta*: implications for host range expansion. *Journal of Pest Science, 92*, 1387–1396.

Tahir, M., Wakil, W., Ali, A., & Sahi, S. T. (2019). Pathogenicity of *Beauveria bassiana* and *Metarhizium anisopliae* isolates against larvae of the polyphagous pest *Helicoverpa armigera*. *Entomologia Generalis, 38*, 225–242.

Urbaneja-Bernat, P., Bru, P., González-Cabrera, J., Urbaneja, A., & Tena, A. (2019). Reduced phytophagy in sugar-provisioned mirids. *Journal of Pest Science, 92*, 1139–1148.

Van Driesche, R., Hoddle, M., & Center, T. (2008). *Control of pests and weeds by natural enemies: an introduction to biological control*. Oxford: Blackwell Publishing.

Van Lenteren, J. C., Bolckmans, K., Kohl, J., Ravensberg, W. J., & Urbaneja, A. (2018a). Biological control using invertebrates and microorganisms: plenty of new opportunities. *BioControl, 63*, 39–59.

Van Lenteren, J. C., Bueno, V. H. P., Calvo, F. J., Calixto, A. M., & Montes, F. C. (2018b). Comparative effectiveness and injury to tomato plants of three neotropical mirid predators of *Tuta absoluta* (Lepidoptera: Gelechiidae). *Journal of Economic Entomology, 111*, 1080–1086.

Verheggen, F., & Fontus, B. (2019). First record of *Tuta absoluta* in Haiti. *Entomologia Generalis, 38*, 349–353.

Wanumen, A. C., Carvalho, G. A., Medina, P., Viñuela, E., & Adán, A. (2016). Residual acute toxicity of some modern insecticides toward two mirid predators of tomato pests. *Journal of Economic Entomology, 1109*, 1079–1085.

Zappalà, L., Biondi, A., Alma, A., Al-Jboory, I. J., Arnò, J., et al. (2013). Natural enemies of the South American moth, *Tuta absoluta*, in Europe, North Africa and Middle-East, and their potential use in pest control strategies. *Journal of Pest Science, 86*, 635–647.

Zarrad, K., Chaieb, I., Tayeb, W., Chraief, I., Laarif, A., Hammami, M., & Haouala, R. (2013). Bio-insecticidal potential of essential oils of two citrus species against two greenhouse pests *Tuta absoluta* Meyrick and *Spodoptera littoralis* Boisduval. *Microbiologie et Hygiène Alimentaire, 25*, 84–88.

Zouba, A., & Mahjoubi, K. (2010). Biological control of *Tuta absoluta* (Lepidoptera: Gelechiidae) with release of *Trichogramma cacoeciae* (Hymenoptera: Trichogrammatidae) in tomato greenhouses in Tunisia. *African Journal of Plant Science and Biotechnology, 4*, 85–87.

Zouba, A., Chermiti, B., Chraiet, R., & Mahjoubi, K. (2013). Effect of two indigenous *Trichogramma* species on the infestation level by tomato miner *Tuta absoluta* in tomato greenhouses in the south-west of Tunisia. *Tunisian Journal of Plant Protection, 8*, 87–106.