Journal of Plant Diseases and Protection (2018) 125:357–364
https://doi.org/10.1007/s41348-018-0164-6

ORIGINAL ARTICLE

# Compatibility of insecticides and *Elachertus inunctus* Nees (Hymenoptera: Eulophidae) for controlling *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) in greenhouse condition

**Fatemeh Yarahmadi**[1] · **Zohreh Salehi**[1] · **Hossein Lotfalizadeh**[2]

Received: 29 July 2017 / Accepted: 24 April 2018 / Published online: 14 May 2018

## Abstract

South American Tomato Pinworm (SATP), *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae), is one of the most devastating pests in tomato greenhouses. Efficacy of some chemical and biorational insecticides, namely chlorfenapyr, thiocyclam, azadirachtin and *Bacillus thuringiensis* (Bt), in controlling SATP and their compatibility with *Elachertus inunctus*, a new SATP larval ectoparasitoid, were studied under greenhouse conditions. For this purpose, larval mortality, leaf and fruit damage and parasitism following the different insecticide treatments and after various days from the treatment (DAT) were recorded and compared to untreated control. Results showed that chlorfenapyr had suitable effects on SATP larvae. Although the experiments indicated that the short-term effects of azadirachtin, thiocyclam and Bt were not detrimental to SATP larvae, but their residual effects were significant in the long term. Among the tested insecticides, Bt was more compatible with *E. innunctus* release. Overall, the results suggest that the integration application of Bt with early inundate release of *E. innunctus* can be recommended for suitable and environmentally safe control of SATP in greenhouse tomato.

**Keywords** Parasitic wasps · Bio-insecticides · Tomato leaf miner · IPM

## Introduction

The South American Tomato Pinworm (SATP), *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae), is an invasive pest native to South America, where it is considered one of the most dangerous pests in tomato greenhouse production and in the open field (Yankova 2012). In the last 10 years, SATP has spread and expanded to many regions of the world including Europe, Africa and Asia, causing extensive damage to international tomato trade (Biondi et al. 2018; Campos et al. 2017; Sankarganesh et al. 2017; Sylla et al. 2017; Xian et al. 2017). The presence of *T. absoluta* was reported in Iran (Baniameri and Cheraghian 2012), in Sub-Saharan Africa (Sylla et al. 2017), recently in northern India (Sankarganesh et al. 2017), and now threatening China (Xian et al. 2017), i.e. the biggest tomato world producer. The female usually lays eggs on leaves, stems, and to a lesser extent on fruits. The young larvae mine the leaves or stems producing large galleries and burrow into the fruit. On leaves, the larvae feed only on mesophyll cells, leave the epidermis intact and make irregular leaf mines, which may later become necrotic and affect photosynthesis in the plant (Desneux et al. 2010; Biondi et al. 2018). Damage from this pest throughout the entire growing cycle of tomatoes can significantly reduce both yield and fruit quality by the direct feeding of *T. absoluta* and secondary pathogens that may enter through the wounds made by the insect. In the absence of control strategies, larval feeding damage can reach up to 100% (Desneux et al. 2011; Yankova 2012; Biondi et al. 2018). Chemical control using synthetic insecticides is an effective management tactic for this pest (Guedes and Siqueira

---

✉ Fatemeh Yarahmadi
yarahmadi@ramin.ac.ir

Hossein Lotfalizadeh
lotfalizadeh@iripp.ir

[1] Department of Plant Protection, Faculty of Agriculture, Khuzestan Agricultural Sciences and Natural Resources University, Ahvaz (Mollasani), Iran

[2] Department of Plant Protection, East-Azarbaijan Research Center for Agriculture and Natural Resources, Tabriz, Iran

2012). Also, the general entophytic behaviour of the larval instars makes it difficult to conduct effective control practices against this pest (Lietti et al. 2005; Guedes and Picanço 2012). Application of the chemicals causes many problems including incensement in production costs, side effects on natural enemy populations, harmful pesticide residues in fruits (Braham and Hajji 2012) and pest resistance to the chemicals (Desneux et al. 2007; Biondi et al. 2018).

Biopesticides in the plant protection systems have the potential to aid the management of the pest (Copping and Menn 2000). Some vegetal products were assessed for potential use in the leaf miner control and can provide a safe control method under organic agricultural conditions. Products with active ingredient azadirachtin possess specific antifeedant and deterrent activities, suppressing and stopping the feeding, reduction of moulting and deformations in pupae and imago, and decrease fecundity in the females (Kleeberg 2001; Isman 2015). Chlorfenapyr is applied against lepidopteran pests. The insecticides were introduced during the 1990s as an alternative to synthetic pyrethroids because of its low toxicity to mammalian and aquatic organisms (Raghavendra et al. 2011). Thiocyclam (Evisect®) is highly efficient in controlling the pest outbreaks (Lietti et al. 2005).

The mixture of spores and protein crystals from pathogen *Bacillus thuringiensis* subsp. *krustaki* Berliner (Bt) is the most widely used microbial insecticide against lepidopteran pests (Wilcox et al. 1986; Peralta and Palma 2017). Bt is not toxic to humans, most beneficial insects, and other nontarget organisms; therefore, it does not cause the serious environmental and safety problems associated with conventional synthetic insecticides (Peralta and Palma 2017).

Genus of *Elachertus* (Hymenoptera: Eulophidae) is primary parasitoids of a variety of lepidopteran larvae. Some species are polyphagous attacking hosts belonging to several different families (Schauff 1985). The parasitoid wasp of *Elachertus inunctus* Nees was originally collected as larval ectoparasitoids of *T. absoluta* on greenhouse tomato in Khouzestan province in the south-west of Iran (Yarahmadi et al. 2016). This parasitoid wasp naturally suppressed SATP larvae on tomato in greenhouse and field conditions in Khuzestan province, south-west of Iran.

The first step in application of a control strategy (chemical control, biological control, etc.) in integrated pest management programme is evaluation of its effectiveness (Pedigo 2002). Also in IPM programmes, biological control agents and the applied pesticides must be compatible with each other (Stark et al. 2007; Desneux et al. 2007). The compatibility of natural enemies to biorational or synthetic insecticides is obviously variable according to the type of the insecticide and species of the natural enemies. Biorational insecticides are efficient to control varied greenhouse pests. Biorational insecticides are also more likely compatible with natural enemies. Compatibility of biorational pesticide with natural enemies is necessary for developing IPM programme (Pedigo 2002).

There has not been any effort to determine efficacies of the bio-insecticides chlorfenapyr, azadirachtin, Bt and *E. inunctus* in control of *T. absoluta* for greenhouse crops. Therefore, the objective of this study was to evaluate the bio-insecticides and parasitoid efficacies against SATP and their integration potential.

## Materials and methods

### Experimental design

The experiment was performed at a commercial greenhouse, with 3000 $m^2$ area, located in Kute Seied Soltan, Ahvaz, Khouzestan province, south-west of Iran (31°27′24″N 48°49′34″E). The greenhouse was cultivated with greenhouse tomato seedlings, Cherry® variety. No insecticide applications were carried out except in experimental treatment. In addition, no herbicides or fungicides were applied in the experimental greenhouse. All growers' practices (growing, fertilizer application, weeding and irrigation of tomato) were used in accordance with the recommendations of the Khuzestan agricultural organization. The experiment was arranged in a randomized complete block design with four replications (125 $m^2$) and 3-metre-wide ridges were made in each. Also, each replication was separated from others by Nylon insect screen (mesh 50, Green-tek®, Canada). The active ingredients, the trade name and doses of the experimental insecticides are given in Table 1. Control was sprayed with water. Treatments were applied using an electronic backpack sprayer (Matabi®, Taizhou Kaide Machinery Co., Ltd.) using the hollow cone, solid spray tip type of nozzle (TXVK-10).

### Parasitoid wasp

The parasitized larvae of *E. inunctus* were collected from infested tomato field of the Veis region, Ahwaz, Khuzestan province (31°30′28″N 48°50′37″). The larvae were transferred to the laboratory and reared in an incubator at temperature 25 ± 1 °C, RH 60% and photoperiod 16:8 (L:D). The parasitoid wasps—five female and five male adults (2 days old) per block—were released 2 weeks after the first observed SATP contamination.

**Table 1** Insecticides, mode of action, trade name and doses of application experimented under tomato greenhouse in 2015

| No. | Treatment | Trade name | Formulation | Mode of action | Applied rate per hectare |
|---|---|---|---|---|---|
| 1 | Azadirachtin[a] (Az) | Neemarin 1500 PPM® | 1% EC | Insect growth regulators | 1 lit |
| 2 | Chlorfenapyr[b] | Crown® | 24% EC | Disrupting the production of adenosine triphosphate | 400 ml |
| 3 | Thiocyclam[c] | Evisect® | 50% SC | Nicotinergic acetylcholine blocker | 500 g |
| 4 | *Bacillus ssp. thuringiensis kurstaki*[b] (Bt) | Belthirul® | 32,000 spore/gr WP | Its delta- endotoxin act as digestive toxin | 0.5 kg |

[a] Biotech international Ltd

[b] Shijiazhuang Awiner Biotech Co., Ltd, China

[c] Biotech international Ltd

## Sampling

The samplings were performed before treatment and 1, 6, 10 and 14 days after treatment (DAT). At each sampling date, six randomly selected plants were checked by travelling in a X-shaped pattern through each plot. Per sampling, 10 leaves were randomly selected from the upper one-third of the plant. The leaves were taken to the laboratory, and alive, dead and parasitized numbers of larvae, as well as the larval mines, were separately recorded under a stereomicroscope. Also, three fruits were randomly picked from each selected plant and numbers of damaged fruits (with wounds made by SATP larvae) were separately recorded in each treatment.

## Data analysis

The mean number of live larvae, leaf mines or damaged fruits per leaf was tested for normality assumption by Kolmogorov–Smirnov test; the data were then arcsine-transformed. The data were statistically analysed by ANOVA. Duncan's multiple range test was used for means separation. All analyses were done using SPSS (Version 16) software (Chicago, IL, USA).

# Results

The efficacy of azadirachtin, chlorfenapyr and thiocyclam against *T. absoluta* in tomato plants under greenhouse conditions with respect to larval mortality, numbers of leaf mines and fruit wounds are presented in Tables 2, 3 and 4.

The highest larval mortality of SATP was recorded in the chlorfenapyr treatment (52.8%) at 1 DAT, while in the other treatments, no significant difference was recorded at 1 DAT (Table 2). Similar results were observed at 6 DAT. However, the SATP larvae mortality in thiocyclam, azadirachtin and Bt treatment was dramatically increased and reached 60, 78.1 and 83.3% respectively, with all of them being significantly higher than control. The data implicated that the azadirachtin, thiocyclam and Bt do not have any significant short-term effects against the pest, but their slower (chronic) effects were sufficient as well as in the case of chlorfenapyr.

The least protective effect against larval leaf damages was observed in thiocyclam, azadirachtin and Bt treatments (Table 3). The leaf mine numbers of the pest were higher than thiocyclam and azadirachtin. These data implicated that thiocyclam and azadirachtin treatments not only had no preventive effect on leaf damages by the pest larvae, but also had an adverse effect on the parasitism and natural control of the pest by *E. inunctus*. Chlorfenapyr significantly reduced the leaf mines at 10 and 15 DAT (34–76%).

All treatments cause significant reduction (83.5–100%) in tomato fruit damages by the larvae (Table 4). However, Bt and azadirachtin (no observed damage) had less damage than chlorfenapyr and thiocyclam (0.2 larval wound per fruit) at 15 DAT.

The larval parasitism of *T. absoluta* by *E. inunctus* ranged between 0 and 19%. The parasitism of SATP larvae was not significantly different at 1 and 6 DAT. But the parasitism ratio was suddenly reduced and reached zero in chlorfenapyr, thiocyclam and azadirachtin treatments at 10 and 14 DAT. The highest activity of the parasitoid wasp was observed in control and Bt treatments (Table 5).

# Discussion

Use of biocontrol agents against pest is an alternative pest management tactic in IPM programmes. But some natural enemies may not always provide economically acceptable biological control for the pest in greenhouses. Therefore, the concurrent use of natural enemies and

**Table 2** Mortality percentages *Tuta absoluta* larvae in the different experimental treatments

| Sampling date | Mean ± SE | | | | | *P* value | $F_{(df)}$ |
|---|---|---|---|---|---|---|---|
| | Chlorfenapyr | Thiocyclam | Azadirachtin | Bt | Control | | |
| 1DAT | 52.8 ± 7.1b* | 10.7 ± 2.9a | 3.5 ± 2.1a | 0 ± 0a | 4.3 ± 2.6a | <0.001 | $33_{(4,25)}$ |
| 6DAT | 62.8 ± 16.8b | 14.3 ± 5.1a | 20.7 ± 7.5a | 25.8 ± 11.2a | 10 ± 10a | 0.02 | $3.729_{(4,25)}$ |
| 10DAT | 70 ± 20b | 60 ± 18.7b | 78.1 ± 6.9b | 83.3 ± 16.6b | 15.2 ± 11.8a | 0.05 | $2.797_{(4,25)}$ |
| 15DAT | 0 ± 0a | 27.3 ± 18.6a | 13.3 ± 9.7a | 0 ± 0a | 0 ± 0a | 0.194 | $1.68_{(4,25)}$ |

* Means followed by the same letter within a row are not significantly different (Duncan test; $P < 0.05$)

**Table 3** Number of leaf mines (per three leaves) in the different experimental treatments

| Sampling date | Mean ± SE | | | | | *P* value | $F_{(df)}$ |
|---|---|---|---|---|---|---|---|
| | Chlorfenapyr | Thiocyclam | Azadirachtin | Bt | Control | | |
| 1DAT | 0.45 ± 5.4a$^{*}$b | 0.68 ± 6.1c | 0.41 ± 2.3a | 0.41 ± .3a | 0.43 ± 4.3ab | <0.001 | $10.3_{(4,20)}$ |
| 6DAT | 0.5 ± 3.06ab | 0.99 ± 4.2b | 0.74 ± 3.4ab | 0.74 ± 3.4ab | 0.5 ± 2.9a | 0.002 | $6.5_{(4,20)}$ |
| 10DAT | 0.3 ± 2.7a | 0.7 ± 3.9b | 0.4 ± 1.2a | 0. 4 ± 1.2a | 0.4 ± 4.9a | <0.001 | $8.2_{(4,20)}$ |
| 15DAT | 0.26 ± 0.66a | 0.4 ± 3.6ab | 0.5 ± 2.2b | 0.5 ± 2.2b | 0.3 ± 3.3ab | <0.001 | $13.5_{(4,20)}$ |

Means followed by the same letter within a row are not significantly different (Duncan test; $P < 0.05$)

**Table 4** Mean of larval wounds (per fruit) in the different experimental treatments

| Sampling date | Larval mortality ± SE | | | | | *P* value | $F_{(df)}$ |
|---|---|---|---|---|---|---|---|
| | Chlorfenapyr | Thiocyclam | Azadirachtin | Bt | Control | | |
| 1DAT | 0.4 ± 6a$^{*}$ | 0 ± 0a | 0 ± 0a | 0 ± 0a | 0 ± 0a | 0.19 | $1.7_{(4,20)}$ |
| 6DAT | 0 ± 0b | 0 ± 0b | 0 ± 0b | 0 ± 0b | 0.4 ± 0.6a | 0.002 | $6.5_{(4,20)}$ |
| 10DAT | 0 ± 0a | 0 ± 0a | 0 ± 0a | 0 ± 0a | 0.4 ± 0.4a | 0.43 | $1_{(4,20)}$ |
| 15DAT | 0.2 ± 0.2b | 0.2 ± 0.2b | 0 ± 0b | 0 ± 0b | 0.8 ± 1.2a | 0.003 | $5.2_{(4,20)}$ |

Means followed by the same letter within a row are not significantly different (Duncan test; $P < 0.05$)

**Table 5** Ratios of parazited larvae (per leaf) by *E. inunctus* in the different experimental treatments

| Sampling date | Larval mortality ± SE | | | | | *P* Value | $F_{(df)}$ |
|---|---|---|---|---|---|---|---|
| | Chlorfenapyr | Thiocyclam | Azadirachtin | Bt | control | | |
| 1DAT | 0 ± 0a | 0.04 ± 0.04a | 0 ± 0a | 0 ± 0a | 0 ± 0a | 0.431 | $1_{(4,20)}$ |
| 6DAT | 0.07 ± 0.04a | 0.08 ± 0.02a | 0.07 ± 0.03a | 0.1 ± 0.06a | 0.13 ± 0.01a | 0.766 | $0.458_{(4,20)}$ |
| 10DAT | 0 ± 0a | 0 ± 0a | 0 ± 0a | 0.09 ± 0.2b | 0.19 ± 0.27b | 0.163 | $1.82_{(4,20)}$ |
| 15DAT | 0 ± 0a | 0 ± 0a | 0 ± 0a | 0.03 ± 0.03ab | 0.11 ± 0.27b | 0.007 | $4.88_{(4,20)}$ |

Means followed by the same letter within a row are not significantly different (Duncan test; $P < 0.05$)

pesticides and their compatibility has studied (Pedigo 2002). A new crop/pest/parasitoid system, i.e. tomato/*T. absoluta*/*E. inunctus*, was used to investigate how the four insecticides (azadirachtin and Bt as biorational and chlorfenapyr and thiocyclam as synthetic insecticides) may affect the pest population, the plant, leaf and fruit damages and activity of the new reported larval parasitoid.

Our greenhouse study showed that chlorfenapyr had suitable acute and chronic effects on SATP larvae. Although it was indicated that acute effects of azadirachtin, thiocyclam and Bt were not detrimental to SATP larvae, but their residual effects were significant in the long term.

Although the product azadirachtin is of vegetable origin, it shows specific effects on the pests. It causes disturbances in basic processes—feeding, metamorphosis and fecundity, followed by lethality (Yankova et al. 2014). Neem-extracted insecticides are known as slow-acting insecticides which is one of the major limitations of these products. The insecticides do not produce an immediate 'knock-down' effect (Isman 2015). Lowerey and Isman (1994) showed that observation time is an important variable in toxicity assessment of neem-extracted products because azadirachtin is a slow-acting insecticide and its antifeedant or growth-inhibitory properties vary depending on the concentration and species of target pest. Similarly, the delayed effect of azadirachtin on *T. absoluta* was previously demonstrated (Braham et al. 2012; Nazarpour et al. 2016). Toxicity of neem-based insecticides against some lepidopteran larvae such as *Cnaphalocrocis medinalis* (Guenée) (Lepidoptera: Pyralidae), *Plutella xylostella* L. (Lepidoptera: Plutellidae) (Liang et al. 2003), *Helicoverpa armigera* Hübner (Lepidoptera: Noctuidae) (Singh et al. 2007), *Lymantria dispar* L. (Lepidoptera: Lymantriidae) (Zabel et al. 2002), *Spodoptera exigua* Hübner (Lepidoptera: Noctuidae) (Greenberg et al. 2005; Yee and Toscano 2014) and *T. absoluta* (Arnò and Gabarra 2011; Braham et al. 2012; Nazarpour et al. 2016) were reported by various researchers.

*Bacillus thuringiensis* has been used as an alternative to synthetic insecticides for decades (Peralta and Palma 2017). The efficacy of the bacterium spores against *T. absoluta* was evaluated in a few studies. For example, the significant effect of *B. thuringiensis* subs. *krustaki* against SATP larvae in tomato fields was previously documented (Nazarpour et al. 2016). Moreover, the efficacy of Bt against SATP larvae and its damage were documented by Gozalez-Caberera et al. (2001), Sabbour and Soleiman (2012), and Nazarpour et al. (2016). In all this research, a lag time was observed between Bt spray and SATP population decrease.

The findings agree with the laboratory experiment results of Silvério et al. (2009), who showed that chlorfenapyr is a good candidate for chemical control of SATP. Also, their study demonstrated that thiocyclam at dosage 60 g $L^{-1}$ showed intermediate efficacy (34% mortality) for SATP control in laboratory condition (Braham et al. 2012). In contrast to our findings, the result of $LD_{50}$ values indicated that chlorfenapyr (3.165%) was less toxic for SATP larvae in comparison with emamectin benzoate (0.461%), imidacloprid (0.621%), indoxacarb (0.753%), profenofos (0.643%), pyridalyl (0.511), methomyl (0.468) and teflubenzuron (1.054%) (Soleiman et al. 2013). This conflict in results may be related to different chemicals used in laboratory experiments of Soleiman et al. (2013) and different methodology of these studies.

The parasitoid wasp, *E. inunctus*, could parasitize up to 19% of SATP larvae. Therefore, the parasitoid wasp alone is not sufficient to control the SATP population in a greenhouse. Possibly the greater release rate of the parasitoid wasp is required for more efficient biological control of the pest in greenhouse tomato. Certainly, integrated application of insecticide (biorational or chemical) with inundate releases of *E. inunctus* is required for sufficient SATP population suppression.

Several commercially available biorational insecticide companies claim that their products are not disruptive to beneficial arthropods. However, research conducted worldwide has shown that biorational insecticides may, in fact, be harmful to certain natural enemies (Biondi et al. 2012a, b, 2013). Although biorational insecticides may not be directly toxic to a particular natural enemy, there may be indirect effects such as delayed development of the host and natural enemy inside, delayed adult emergence and/or decreased natural enemy survivorship (Croft 1990). There is variability apparent in the compatibility of natural enemies to biorational insecticides based on the type of biorational pesticide, whether the natural enemy is a parasitoid or predator, and their developmental stage. Biorational insecticides are effective to control many different types of greenhouse pests (Glare et al. 2012). However, it is important to know which biorational insecticide/miticide is compatible or not compatible with natural enemies in order to avoid disrupting successful biological control programmes (Biondi et al. 2012a, b).

Our results indicated that chlorfenapyr, thiocyclam and azadirachtin have adverse effects on parasitism of SATP larvae by *E. inunctus*. The larval parasitism significantly in Bt treatment was more than other insecticide treatments. Therefore, our finding showed that Bt is the best candidate for integrated control of SATP infestation with *E. inunctus* release. A few studies were conducted on the integrated use of natural enemies and biorational or synthetic insecticides against *T. absoluta* (Mollá et al. 2011; Arnò and Gabarra 2011; Zappalà et al. 2012; Biondi et al. 2013). Similarly, high toxicity of chlorfenapyr on some parasitoid wasps was previously reported (Pietrantonio and Benedict 1999, 1999; Haseeb and Amano 2002; Kapuge et al. 2003; Haseeb et al. 2005; Wang et al. 2014). Also, it was demonstrated that thiocyclam was highly toxic for parasitoids of citrus leaf miner, *Phyllocnistis citrella* Stainton. In contrast to our findings, Ibrahim and Kim (2008) prove that thiocyclam had less toxicity for *Diglyphus isaea* (Walker) (Hymenoptera: Eulophidae). The different parasitic wasp may be a major reason of the conflict in results. In the other hand, *D. isaea* is a widely used biocontrol agent (Saad et al. 2007; Ibrahim and Kim 2008; Abou-Fakhr Hammad and

Mc Auslane 2010) and it may have developed resistance to some chemicals.

Effects of azadirachtin-based insecticides on eulophid parasites were studied by some authors. For example, azadirachtin considered as a harmless insecticide for *Tamarixia triozae* Burks (Hymenoptera: Eulophidae) (Luna-Cruz et al. 2015), *D. mollipla* Holmgren (Akol et al. 2001), *Colpoclypeus florus* Walker (Brunner et al. 2001), *Diglyphus isaea* (Saad et al. 2007) and *D. isaea* (Abou-Fakhr Hammad and Mc Auslane 2010). In agreement with our results, a high toxic effect of azadirachtin on the other species of the family, *Tamarixia radiata* Waterston, was reported by Santos et al. (2015). Biondi et al. (2013) showed that azadirachtin did not have a lethal impact on females of *Bracon nigricans* Szépligeti. However, it causes important delays in population growth.

Hamel (1977) showed that parasitism by *Apanteles fumiferanae* Vier. (Hymenoptera: Braconidae) and *Glypta fumiferanae* Vier. (Hymenoptera: Ichneumonidae), parasitoid wasps of first instar larvae of *Choristoneura occidentalis* Freeman (Lepidoptera: Tortricidae), was significantly higher in treatment blocks following Bt application. But parasitism by *Phaeogenes hariolus* Cresson (Hymenoptera: Ichneumonidae) and *Cermoasia auricaudata* Tns. (Hymenoptera: Ichneumonidae)—parasitoids of late instars and pupae of the pest—was significantly lower following treatment (Hamel 1977). Chilcutt and Tabashnik (1999) showed that there was no effect of Bt treatment on oviposition by *C. plutella*. Similar to our findings, Brunner et al. (2001) demonstrated that Bt products cause no toxicity to *C. florus*. Brunner et al. (2001) suggested that Bt products cause no toxicity to *C. florus*. Similarly, Haseeb et al. (2004) proved that field dosage of Bt causes low adult mortality of *C. plutella*.

Several biocontrol agents and integrated pest management programmes (IPMs) have been recently evaluated for control of SATP (Zappalà et al. 2012). Biocontrol agents (predators, parasitoids or pathogens) are considered one possible solution to the *T. absoluta* crisis (Desneux et al. 2010). This strategy offers a more sustainable and less expensive alternative to chemicals (Urbaneja et al. 2013).

In conclusion, chlorfenapyr was the best insecticide for control of SATP larvae and its damage to tomato leaves and fruits. But the insecticide was not compatible with parasitoid wasp, *E. inunctus*. Among the insecticides tested, Bt was more compatible with *E. innunctus* release. Also, Bt had no significant short-term effect on SATP population. Therefore, integrated application of Bt with early inundate release of *E. innunctus* was recommended for suitable and environmentally safe control of SATP in greenhouse tomato. The results of this study can be used in the IPM programme of tomato greenhouses.

**Acknowledgements** This research was supported by research deputy of Khuzestan Agricultural Sciences and Natural Resources University [Grant Number 941/09].

## References

Abou-Fakhr Hammad EM, McAuslane HJ (2010) Effect of *Melia azedarach* L. extract on *Liriomyza sativae* (Diptera: Agromyzidae) and its biocontrol agent *Diglyphus isaea* (Hymenoptera: Eulophidae). J Food Agric Environ 8(34):1247–1252

Akol AM, Sithanatham S, Varela AM, Mueke JM, Okelo RO (2001) Evaluation of two neem insecticides for non-target effects on the larval parasitoids of the diamondback moth, *Plutella xylostella* (L.). In: Proceeding of the 41th international workshop; Melbourne, Australia, November 26–29

Arnò J, Gabarra R (2011) Side effects of selected insecticides on the *Tuta absoluta* (Lepidoptera: Gelechiidae) predators *Macrolophus pygmaeus* and *Nesidiocoris tenuis* (Hemiptera: Miridae). J Pest Sci 84(4):513–520. https://doi.org/10.1007/s10340-011-0384-z

Baniameri V, Cheraghian A (2012) The current status of *Tuta absoluta* in Iran and initial control strategies. In: EPPO/IOBC/FAO/NEPPO joint international symposium on management of *Tuta absoluta* (tomato borer). Agadir, Morocco, November 16–18

Biondi A, Desneux N, Siscaro G, Zappala L (2012a) 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. https://doi.org/10.1016/j.chemosphere.2011.12.082

Biondi A, Mommaerts V, Smagghe G, Viñuela E, Zappalá L, Desneux N (2012b) The non-target impact of spinosyns on beneficial arthropods. Pest Manag Sci 68(12):1523–1536

Biondi A, Zappalá L, 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. https://doi.org/10.1371/journal.pone.0076548.eCollection

Biondi A, Guedes RNC, Wan FH, Desneux N (2018) Ecology, worldwide spread and management of the invasive South American Tomato Pinworm, *Tuta absoluta*: past, present, and future. Ann Rev Entomol 63:239–258. https://doi.org/10.1146/annurev-ento-031616-034933

Braham M, Hajji L (2012) Management of *Tuta absoluta* (Lepidoptera, Gelechiidae) with insecticides on tomatoes. In: Perveen F (ed) Insecticides pest engineering. In Tech, Rijeka, pp 333–354

Braham M, Glida-Gnidez H, Hajji L (2012) Management of the tomato borer, *Tuta absoluta* in Tunisia with novel insecticides and plant extracts. OEPP/EPPO Bull 42(2):291–296. https://doi.org/10.1111/epp.2572

Brunner JF, Dunley JE, Doerr MD, Beers EH (2001) Effect of pesticides on *Coloclypeus florus* (Hymenoptera: Eulophidae) and *Trichogramma platneri* (Hymenoptera: Trichogrammatidae) parasitoids of leafrollers in Washington. J Econ Entomol 94(5):1072–1084. https://doi.org/10.1603/0022-0493-94.5.1075

Campos MR, Biondi A, Adiga A, Guedes RNC, Desneux N (2017) From the western palaearctic region to beyond: *Tuta absoluta* ten years after invading Europe. J Pest Sci 90:787–796. https://doi.org/10.1007/s10340-017-0867-7

Chilcutt CF, Tabashnik BE (1999) Effects of *Bacillus thuringiensis* on adults of *Cotesia plutellae* (Hymenoptera: Braconidae), a parasitoid of the Diamondback Moth, *Plutella xylostella* (Lepidoptera: Plutellidae). Biocontrol Sci Technol 9(3):435–440. https://doi.org/10.1080/09583159929695

Cloyd R (2005) Compatibility conflict: Is the use of biological control agents with pesticides a viable management strategy? In: Second international symposium on biological control of arthropods; Davos, Switzerland, September 12–16

Cloyd R (2005) Compatibility conflict: is the use of biological control agents with pesticides a viable management strategy? In: Second international symposium on biological control of arthropods, Compiler, University of California, Riverside, USA

Copping LG, Menn JJ (2000) Biopesticides: a review of their mode of action and efficacy. Pest Manag Sci 56:651–676. https://doi.org/10.1002/1526-4998(200008)56:8<651:AID-PS201>3.0.CO;2-U

Croft BA (1990) Arthropod biological control agents and pesticides. Wiley Interscience, New York

Desneux N, Decourtye A, Delpuech JM (2007) The sublethal effects of pesticides on beneficial arthropods. Annu Rev Entomol 52:81–106. https://doi.org/10.1146/annurev.ento.52.110405.091440

Desneux N, Wajnberg E, Wyckhuys KAG, Burgio G, Arpaia S, Narvez-Vasquez CA, Gonalez-Cabrera J, Catalan Ruescas D, Frandon TE (2010) Biological invasion of European tomato crops by *Tuta absoluta*: Ecology, geographic expansion and prospects for biological control. J Pest Sci 83(3):197–215. https://doi.org/10.1007/s10340-010-0321-6

Desneux N, Luna MG, 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. J Pest Sci 84:403–408

Glare T, Caradus J, Gelerner W, Jackson T, Keyhani N, Kohl J, Marrone P, Morin L, Stewart A (2012) Have biopesticides come of age? Trends Biotech 30(5):250–258. https://doi.org/10.1016/j.tibtech.2012.01.003

Gozalez-Caberera J, Mollá O, Monton H, Urbaneja A (2001) Efficacy of *Bacillus thuringiensis* (Berliner) in controlling the tomato borer, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). Biocontrol 56:71–80. https://doi.org/10.1007/s10526-010-9310-1

Greenberg SM, Showler AT, Liu TX (2005) Effects of neem-based insecticides on beet armyworm (Lepidoptera: Noctuidae). Insect Sci 12(1):17–23. https://doi.org/10.1111/j.1672-9609.2005.00003.x

Guedes RNC, Picanço MC (2012) The tomato borer *Tuta absoluta* in South America: pest status, management and insecticide resistance. EPPO Bull 42(2):211–216. https://doi.org/10.1111/epp.2557

Guedes RNC, Siqueira HAA (2012) The tomato borer *Tuta absoluta*: insecticide resistance and control failure. CAB Rev 7(55):1–7

Hamel DR (1977) The effects of Bacillus thuringiensis on parasitoids of the western spruce budworm, Choristoneura occidentals (Lepidoptera: Tortricidae), and the sprouce coneworm, Dioryctеia reniculelloids (Lepidoptera: Pyralidae) in montana. Cana Entomol 109(11):1409–1415

Haseeb M, Amano H (2002) Effects of contact, oral and persistent toxicity of selected pesticides on *Cotesiaplutellae* (Hym., Braconidae), a potential parasitoid of *Plutella xylostella* (Lep., Plutellidae). J App Entomol 126(1):8–13. https://doi.org/10.1046/j.1439-0418.2002.00596.x

Haseeb M, Liu TX, Jones WA (2004) Effects of selected insecticides on Cotesia plutellae, endoparasitoid of Plutella xylostella. BioContr 49(1):33–46. https://doi.org/10.1023/B:BICO.0000009377.75941.d7

Haseeb M, Amano H, Liu TX (2005) Effects of selected insecticides on Diadegma semiclausum (Hymenoptera: Ichneumonidae) and Oomyzus sokolowskii (Hymenoptera: Eulophidae), parasitoids of Plutella xylostella (Lepidoptera: Plutellidae). Insect Sci 12(3):163–170. https://doi.org/10.1111/j.1005-295X.2005.00020.x

Ibrahim AM, Kim Y (2008) Transient expression of protein tyrosine phosphatases encoded in Cotesia plutellae bracovirus inhibits insect cellular immune responses. Naturwissenschaften 95(1):25–32. https://doi.org/10.1007/s00114-007-0290-7

Isman MB (2015) A renaissance for botanical insecticides? Pest Manag Sci 71(12):1587–1590. https://doi.org/10.1002/ps.4088

Kapuge S, McDougall S, Hoffmann AA (2003) Effects of methoxyfenozide, indoxacarb, and other insecticides on the beneficial egg parasitoid Trichogramma nr. brassicae (Hymenoptera:Trichogrammatidae) under laboratory and field conditions. J Econ Entomol 96(4):1083–1090. https://doi.org/10.1603/0022-0493-96.4.1083

Kleeberg H (2001) NeemAzal-T/S a botanical product for efficient control of insect pests. In: Soares de Faria R, Kleeberg H (eds) Practice oriented results on use and production of plant extracts and pheromones in integrated and biological pest control. Proc. 2nd workshop "neem and pheromones". Trifolio-GmbH, Lahnau, pp 28–35

Liang GM, Chen W, Liu TX (2003) Effects of three neem-based insecticides on diamondback moth (Lepidoptera: Plutellidae). Crop Protec 22(2):333–340. https://doi.org/10.1016/S0261-2194(02)00175-8

Lietti M, Botto E, Alzogaray RA (2005) Insecticide resistance in Argentine populations of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae). Neotrop Entomol 34:113–119. https://doi.org/10.1590/S1519-566X2005000100016

Lowerey DT, Isman MB (1994) Insect growth regulating effects of neem extract and azadirachtin on aphids. Entomol Exp Appl 72:77–84. https://doi.org/10.1111/j.1570-7458.1994.tb01804

Luna-Cruz A, Rodriguez-Leyva E, Lomeli-Flores JR, Ortega-Arenas DL, Bautista-Martinez N, Pineda S (2015) Toxicity and residual activity of insecticides against *Tamarixia triozae* (Hymenoptera: Eulophidae), a parasitoid of *Bactericera cockerelli* (Hemiptera: Triozidae). J Econ Entomol 108(5):2289–2295. https://doi.org/10.1093/jee/tov206

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. J Crop Protec 5(3):331–342. https://doi.org/10.18869/modares.jcp.5.3.331

Pedigo LP (2002) Entomology and pest management. Iowa University Press, Iowa City

Peralta C, Palma L (2017) Is the insect world overcoming the efficacy of *Bacillus thuringiensis*? Toxins 9:39. https://doi.org/10.3390/toxins9010039

Pietrantonio PV, Benedict JH (1999) Effect of new cotton insecticide chemistries, tefenozide, spinosad and chlorfenapyr, on *Orius insidiosus* and two *Cotesia* species. Southwest Entomol 24(1):21–29

Raghavendra K, Barik TK, Sharma P, Bhatt RM, Srivastava HC, Sreehari U, Dash AP (2011) Chlorfenapyr: a new insecticide with novel mode of action can control pyrethroid resistant malaria vectors. Malar J 10:16. https://doi.org/10.1186/1475-2875-10-16

Saad AS, Massoud MA, Abdel-Mageed AA, Hamid NA, Mourad AK, Barakat AS (2007) Abamectin, pymetrozine and azadirachtin sequence as a unique solution to control the leafminer *Liriomyza* trifolii (Burgess) (Diptera: Agromyzidae) infesting garden beans (*Phaseolus vulgaris* L.) in Egypt. Commun Agri Appl Biol Sci 72(3):583–593

Sabbour MM, Soleiman N (2012) Evaluations of three *Bacillus thuringiensis* against *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Egypt. Int J Sci Res 3(8):2067–2073. https://doi.org/10.13140/RG.2.1.3355.37652015-07-22T15:25:42UTC

Sankarganesh E, Firake DM, Sharma B, Verma VK, Behere GT (2017) Invasion of South American Tomato Pinworm, *Tuta* *absoluta*, in northeastern India: a new challenge and biosecurity concerns. Entomol Gen 36(4):335–345

Santos MS, Zanardi OZ, Pauli KS, Forim MR, Yamamoto PT, Vendramim JD (2015) Toxicity of an azadirachtin-based biopesticide on *Diaphorina citri* Kuwayama (Hemiptera: Liviidae) and its ectoparasitoid *Tamarixia radiata* (Waterston) (Hymenoptera: Eulophidae). Crop Protec 74:116–123. https://doi.org/10.1016/j.cropro.2015.04.015

Schauff ME (1985) Taxonomic study of the Nearctic species of *Elachertus* Spinola (Hymenoptera: Eulophidae). Proc Entomol Soc Wash 87(4):843–858

Silvério FO, de Alvarenga ES, Moreno SC, Picanço MC (2009) Synthesis and insecticidal activity of new pyrethroids. Pest Manage Sci 65:900–905. https://doi.org/10.1002/ps.1771

Singh G, Rup PJ, Koul O (2007) Acute, sublethal and combination effects of azadirachtin and *Bacillus thuringiensis* toxins on *Helicoverpa armigera* (Lepidoptera: Noctuidae) larvae. Bull Entomol Res 97(4):351–357. https://doi.org/10.1017/S0007485307005019

Soleiman MMM, Abdel-Moniem ASH, Abdel-Rahim HA (2013) Impact of some insecticides and their mixtures on the population of tomato borers, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) and *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae) in tomato crop at upper Egypt. Arch Phytopathol Plant Protect 47(14):1764–1776. https://doi.org/10.1080/03235408.2013.857226

Stark JD, Vargas R, Banks JE (2007) Incorporating ecologically relevant measures of pesticide effect for estimating the compatibility of pesticides and biocontrol agents. J Econ Entomol 100:1027–1032. https://doi.org/10.1603/0022-0493(2007)100[1027:IERMOP]2.0.CO;2

Sylla S, Brévault T, Bal AB, Chailleux A, Diatte M, Desneux N, Diarra K (2017) Rapid spread of the tomato leafminer, *Tuta absoluta* (Lepidoptera: Gelechiidae), an invasive pest in Sub-Saharan Africa. Entomol Gen 36(3):269–283

Urbaneja A, Desneux N, Gabarra R, Arno J, González-Cabrera J, Mafra-Neto A, Pinto ADS, Parra JRP (2013) Biology, ecology and management of the tomato borer, *Tuta absoluta*. In: Peña JE (ed) Potential invasive pests of agricultural crops. CABI Series, Wallingford, pp 98–125. https://doi.org/10.1079/9781845938291.0098

Vasconcelos GR (2013) Strain selection and host effect on *Trichogramma pretiosum* Riley, 1879 (Hymenoptera: Trichogrammatidae) quality for *Tuta absoluta* (Meyrick, 1917(Lepidoptera: Gelechiidae) control in tomato crops. Dissertation, University of Moura Lacerda, Brazil

Wang SS, Guo ZL, Lio YL (2014) Acute toxicities and sublethal effects of some conventional insecticides on *Trichogramma chilonis* (Hymenoptera: Trichogrammatidae). J Econ Entomol 105(4):1157–1163. https://doi.org/10.1603/EC12042

Wilcox D, Shivakumar B, Melin MF, Miller TA, Benson CW, Shopp D, Casuto GJ, Gundling TJ, Bolling BB, Spear JL (1986) Genetic engineering of bio insecticides. In: Inouye M, Sarma R (eds) Protein engineering: applications in science, medicine, and industry. Academic, Orlando, pp 395–413

Xian X, Han P, Wang S, Zhang G, Liu W, Desneux N, Wan F (2017) The potential invasion risk and preventive measures against the tomato leafminer *Tuta absoluta* in China. Entomol Gen 36(4):319–333

Yankova V (2012) Damage caused by tomato leaf miner (*Tuta absoluta* Meyrick) in tomato varieties grown in greenhouse. Plant Sci 49:92–97

Yankova V, Valchev N, Markova D (2014) Effectiveness of phytopesticide Neem Azal T/S against tomato leaf miner (*Tuta absoluta* Meyrick) in greenhouse tomato. Bulg J Agric Sci 20:1116–1118

Yarahmadi F, Salehi Z, Lotfalizadeh H (2016) Two species of the genus *Elachertus* Spinola (Hym.: Eulophidae) new larval ectoparasitoids of *Tuta absoluta* (Meyreck) (Lep.: Gelechidae). J Crop Protect 5(3):413–418

Yee WL, Toscano NC (2014) Laboratory evaluations of synthetic and natural insecticides on beet armyworm (Lepidoptera: Noctuidae) damage and survival on lettuce. J Econ Entomol 91(1):56–63. https://doi.org/10.1093/jee/91.1.56

Zabel A, Manojlovic B, Rajkovic S, Stankovic S, Kostic M (2002) Effect of Neem extract on *Lymantria dispar* L. (Lepidoptera: Lymantriidae) and *Leptinotarsa decemlineata* Say. (Coleoptera: Chrysomelidae). J Pest Sci 75(1):19–25. https://doi.org/10.1046/j.1439-0280.2002.02006.x

Zappalà L, Bernardo U, Biondi A, Cocco A, Deliperi S, Delrio G, Giorgini M, Pedata P, Rapisarda C, Garzia GT, Siscaro G (2012) Recruitment of native parasitoids by the exotic pest *Tuta absoluta* in Southern Italy. Bull Insectology 65(1):51–61