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Editorial

Research toward enhancing integrated management of *Tuta absoluta*, an ongoing invasive threat in Afro-Eurasia

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1 Introduction

The South American tomato pinworm, *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae), originating from Peru (Guillemaud et al. 2015), has invaded over 110 countries and posed a major threat to tomato production in Afro-Eurasia since its first detection in Spain in 2006 (Desneux et al. 2010, 2011; Mansour et al. 2018; Biondi et al. 2018; Han et al. 2019a; Verheggen & Fontus 2019; Desneux et al. 2022). Nowadays, we have reached a consensus that the cryptic nature of the larvae, high reproductive potential with multiple overlapping generations, ability to do parthenogenesis, and moderate or high resistance to commonly used insecticides (Biondi et al. 2018; Guedes et al. 2019) make it difficult for growers to adopt effective Integrated Pest Management (IPM) packages. An earlier review by Desneux et al. (2022) has provided a global picture on the practical implementations of various IPM options against *T. absoluta* across different world regions. Although these IPM tools may differ from continent to continent, it has been observed that, in general, existing biorational tactics are still too expensive for widespread application or need to be further developed to higher Technological Readiness Levels (TRLs) so that they can be more widely adopted in practice in the fields. The optimization of existing IPM tools and practices, as well as the development of innovative, sustainable management approaches are urgently needed to successfully achieve this goal. This is notably important for the newly-invaded regions where substantial economic losses and severe environmental impacts have been reported. For instance, *T. absoluta* continues to spread in Asia, where local growers are increasingly experiencing severe damage to tomato and other economically important solanaceous crops (e.g. potato and eggplant). In this context, this special issue aims to provide a timely collection of recent advances in IPM of *T. absoluta*.

2 Basic bio-ecology

Even though the basic bio-ecology characteristics of *T. absoluta* have been fully documented (Biondi et al. 2018), we obtained more information on this aspect in this collection. Caruso et al. (2024) demonstrated for the first time that *T. absoluta* can carry an infectious primary inoculum of Tomato brown rugose fruit virus (ToBRFV), one of the most important threats to tomato crops worldwide. This finding is timely and it highlights the potential epidemiological role of *T. absoluta* in spreading ToBRFV in the field. Such a "double-risk" to tomato crops shall alert quarantine procedures and growers worldwide. Ismoilov et al. (2024) showed an opportunistic cannibalism mode in *T. absoluta* in laboratory trials. Such an adaptive behavior could help to maintain its population when plant food is scarce. Besides biotic factors, abiotic factors may also have a strong influence on the population establishment and growth. Liu et al. (2023) showed that protected agricultural facilities (e.g. greenhouses) may favor the year-round persistence of *T. absoluta* in China where it should not. Therefore, IPM should be simultaneously implemented inside and outside protected facilities such as tunnels and greenhouses for the rational management. As indoor and outdoor conditions vary substantially, growers may adopt different management strategies. Indeed, an earlier study provided evidence that host plant, temperature and relative humidity are factors that greatly influence key biological parameters of *T. absoluta* (Cherif et al. 2019).

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3 Management

Chemical control is still the key component of IPM packages for *T. absoluta*. However, different risks need to be considered in fields. For example, Ullah et al. (2024) were the first to investigate spinosad-induced intergenerational sublethal effects on *T. absoluta* at the biological and molecular levels. The insecticide resistance-related genes were upregulated in spinosad-treated groups in the parental and progeny generations compared to the control group. The observed high selection pressure may partially explain the rapid evolution of spinosad resistance in the pest. Therefore, alternating insecticides is crucial to delay resistance. Broflanilide, a novel meta-diamide insecticide, showed strong lethal, sublethal and transgenerational effects on *T. absoluta* (Qu et al. 2023). Low concentrations of broflanilide can suppress the pest population by affecting their longevity, fecundity, and development. Still, more studies are needed to fully assess its non-target effects on beneficial arthropods, including pest's natural enemies. In this collection, Mesak et al. (2024) assessed the potential side effects of two diamides (chlorantraniliprole and flubendiamide) on a mirid predator. They found that chlorantraniliprole and flubendiamide are generally safe for the predator, but the use of flubendiamide deserves greater attention because it reduces the fecundity of progeny obtained from the treated predators. The sublethal effects of chemical insecticides on a wide range of beneficial arthropods in agroecosystems have long been considered a key issue for insecticide risk assessment (Desneux et al. 2007).

Biological control using arthropods, including parasitoids and/or predators, is a major part of this special issue. Thelytokous strains of the parasitoid *Neochrysocharis formosa* (Westwood) (Hymenoptera: Eulophidae), a host-feeding larval parasitoid, have been shown to have better biocontrol potential than arrhenotokous strains against *T. absoluta* (Wang et al. 2024a). Host feeding has previously been shown to be a key factor in host mortality (Zhang et al. 2021; 2022). Importantly, this species can also attack several exotic leafminers, such as *Liriomyza sativae* (Blanchard), *L. huidobrensis* (Blanchard), and *L. trifolii* (Burgess) (Diptera: Agromyzidae) in Asia. Plant-derived food sources are the main sources of carbohydrates and protein for parasitoids in the field. Urbaneja-Bernat et al. (2024) showed that *Lobularia maritima* L. (Brassicaceae) is a nutrient-rich floral food source for the parasitoid *Dolichogenidea gelechiidivoris* (Marsh) (Hymenoptera: Braconidae), aside *Necremnus tutae* Ribes & Bernardo (Hymenoptera: Eulophidae) (Arnó et al. 2018). These findings can further promote conservation biological control programs of *T. absoluta* in tomatoes and enhance establishment of released parasitoids on the crop. Egg parasitoids are also addressed in this collection. Jiang et al. (2024a) assessed the biocontrol potential of three native *Trichogramma* species (*T. chilonis* (Ishii), *T. dendrolimi* Matsumura, and *T. ostriniae* Pang and Chen (Hymenoptera: Trichogrammatidae)) on *T. absoluta* under controlled laboratory conditions. They concluded that *T. ostriniae* was the most promising biocontrol species for *T. absoluta*. However, another companion study by Li et al. (2024) showed different results as they identified *T. chilonis* as the most effective species parasitizing the eggs of *T. absoluta*. The inconsistent results may be due to the bioassay methods used. Biological control based on other principles, such as Sterile Insect Technique (SIT), RNA interference (RNAi), and botanical insecticides are discussed in this special issue. Diya et al. (2024) assessed the toxic effects of an inhibitory cystine knot peptide extracted from pea seeds, and they showed promising results. They demonstrated that PA1b is toxic against *T. absoluta* when delivered through injection. As vitellogenin (Vg) plays a vital role in female reproduction, Yang et al. (2023) demonstrated that co-silencing two Vg genes by RNAi significantly inhibited the ovarian development and reduced the fecundity of *T. absoluta*. This paves the way for the development of RNAi-based insecticides. The optimal dose of gamma radiation was screened to produce sterile but competitive males for SIT programs (Zhou et al. 2023), demonstrating some potential of this classical technology in the field. Future studies could investigate whether the radiation treatment could lead to stronger males, as this could increase the efficacy of such a tactic. Indeed, in this special issue, one study shows that *T. absoluta* females prefer males with higher reproductive quality (young, virgin and heavy) and that the male's body weight has a direct influence on the increased longevity and reproductive performance of females (Gonçalves et al. 2024).

Agronomic control strategies are straightforward and easy-for-adoption by growers, and they could have a significant impact on *T. absoluta* populations if properly used. Kumaraswamy et al. (2024) compared the antixenosis and antibiosis resistance in wild and cultivated tomatoes for *T. absoluta*. The findings hint the importance of understanding resistance traits in wild accessions to control insects with different feeding modes (*T. absoluta* and *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae)), which will allow us to develop multiple insect-resistant tomato cultivars. Besides tomato, potato is another major crop threatened by *T. absoluta* infestation. Yang et al. (2024) provided new information on how the bottom-up effects of different potato cultivars could influence the performance of *T. absoluta*. Thus, the resistant cultivars should be included in the IPM programs in potato production. Modulation of fertilization could also trigger strong bottom-up effects on pest prevalence via multitrophic interactions (Dong et al. 2018; Becker et al. 2021; Han et al. 2019b, 2020, 2022). Interestingly, in this special issue, we find empirical and modelling studies addressing this aspect. Konan et al. (2024) demonstrated that interactions between mirid predators and fertilization management are important in tomato agro-ecosystems for developing sustainable IPM strategies targeting *T. absoluta* and *B. tabaci* in tomatoes. This study provides important

information on the complementarity of zoophytophagous predators as biocontrol agents for multiple pests, and it also highlights the importance of considering optimal fertilization in the implementation of IPM strategies. A modelling study by Bevacqua et al. (2024a) used life history theory to explain the observed plasticity in *T. absoluta* age and size at pupation under stressful environmental conditions. Another interesting modelling study from the same team showed the combined effects of different temperature, fertilization/irrigation (fertigation), and biocontrol scenarios on plant growth and the overall health of the production system (Bevacqua et al. 2024b). We call for more such in-field and modelling studies in the future as this could provide convincing evidences. This aspect has been recently advocated by a novel theoretical framework (Multidimensional Management of Multiple Pests, 3MP) (Han et al. 2024).

Other aspects related to behavioral management are addressed in this special issue. Sun et al. (2024) demonstrated that *Rosmarinus officinalis* L. (Lamiaceae) can act as a promising repellent plant against *T. absoluta*. Volatile organic compounds (VOCs) play a crucial role in such an antixenosis. By analyzing the diversity of VOC profiles from a variety of domesticated tomato plants and wild relatives, Amegan et al. (2024) highlighted the importance of inter- and intra-specific diversity of VOCs in antixenosis to *T. absoluta*. This study advocates an inter-disciplinary approach, bridging chemical ecology with phylogenetic analyses when screening anti-herbivore plant defenses. Besides olfactory cues, visual cues are also important in the development of control tactics. Jiang et al. (2024b) identified the expression and function of opsin genes related to the phototactic behavior in *T. absoluta*. It is possible to develop novel control tactics by disrupting this behavior, which is essential for mate searching, food foraging and oviposition site selection. Despite this pest has been shown to be polygyny (Wang et al. 2021), *Wolbachia* in its populations may not lead to either parthenogenesis or failure of pheromone-based strategies (Erasmus et al. 2022).

Last, but not least important, a timely review on the current distribution, damage, management, and research on the IPM of *T. absoluta* in China is provided in this special issue (Wang et al. 2024b). This review is important as China is the world's largest producer of tomatoes. The introduced populations in Northwest and Southwest China are assumed to be the source for the present nationwide distribution (Wang et al. 2023). Despite many applied research efforts have been made since its invasion into China in 2017, the practical adoption of green tactics within IPM packages has been limited due to the low cost-effectiveness. The low TRLs of the existing IPM tactics and the lack of subsides for growers shall be addressed to increase the adoption of those green tactics, such as biological control, enhanced biological control using functional plants, push-pull strategies, and RNAi-based control. For growers, clear Economic Injury Levels (EILs) shall be determined based on their own goal for markets as damage shall be prevented before it reaches the EILs (Rostami et al. 2020).

4 Conclusion

We appreciate the valuable contributions from all the authors to this timely special issue in *Entomologia Generalis*. It is indeed timely because *T. absoluta*, as a devastating pest, is still expanding its invasion range and threatening worldwide tomato production. The recent advances in various aspects of its bio-ecology and management, emphasized and discussed in this special issue, shall provide ample information for researchers, extension advisors and growers who are expecting greener IPM packages for this pest. Ultimately, this shall be a valuable contribution to the effective, sustainable crop protection while providing environmental benefits and strengthening vital ecosystem services.

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