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REVIEW

Tuta absoluta continues to disperse in Asia: damage, ongoing management and future challenges

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Abstract

Since its initial detection in Turkey in 2009, the invasive destructive pest South American tomato pinworm *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) has started its new invasion journey to east and invaded most Asian countries. This pest currently causes extensive damage to tomato production and potentially threatens key production areas such as China. To provide an overview of current status of *T. absoluta* in Asia, we have briefly reviewed the damage and economic impacts by this pest locally and discussed why this species has spread so rapidly among the countries. Moreover, ongoing integrated pest management options are summarized in newly invaded areas with an emphasis of discussing the potential control failures by chemical insecticides. Future research efforts on developing promising management technologies are recommended. Finally, we suggest building a cross-regional network to enhance the sustainable control of this pest.

Keywords Invasive pest · Quarantine · Chemical control · Biological control · Genetically modified crops · RNA interference · Sterile insect technique · Cross-regional network

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Key message

- *Tuta absoluta* has arrived in almost all the Central and Southwest Asian countries neighbouring China, the world's largest tomato-producing country.
- Ineffectiveness of early surveillance network, weak quarantine efforts and increasing trade may have favoured its rapid spread among Asian countries.
- Various IPM components are available, and management failure by chemical control is predicted to appear in future.
- A cross-regional network should be built by gathering the researchers from infested and un-infested areas in order to reach a sustainable control of the moth globally.

Introduction

The South American tomato pinworm *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae) is an invasive, destructive pest. Originated in Peru and introduced from a single initial Chilean population to Europe (Guillemaud et al. 2015), it was firstly detected in eastern Spain in 2006 and continued its spread process in Afro-Eurasia (Desneux et al. 2010, 2011; Biondi et al. 2018). It has become a serious threat to tomato production in both greenhouse and open-field crops worldwide. This pest was spreading rapidly in Europe and continued its invasion in eastern areas despite the plant protection agencies' efforts in different countries. Estimations show that *T. absoluta* increased its range radius by an average of 600 km per year (Campos et al. 2017). After the first detection of *T. absoluta* in 2009 in Turkey (Kilic 2010), it started its new invasion journey to eastern areas in Asia. Until recently, it has arrived in almost all the Central and Southwest Asian countries neighbouring China (Biondi et al. 2018). Among the ten largest world tomato producers, three countries, China, India and Turkey, account for almost half of the land area covered worldwide with tomato crops, i.e. 31, 11 and 7%, respectively (Desneux et al. 2011). Unfortunately, this pest is present in Turkey and India, while China, as the key production area, is currently facing a high invasion risk (Kilic 2010; Kalleshwaraswamy et al. 2015; Shashank et al. 2015; Xian et al. 2017; Han et al. 2018). Therefore, in this paper, we have summarized and updated the knowledge of the ecological and economic impacts of this pest on the countries after its invasion in Asia, and discussed the potential reasons of such a rapid spread in these countries. Moreover, ongoing integrated management options in invaded areas are reviewed. Finally, we recommend the existing successful management efforts and call for research and development on new promising management tools. The aim of this review is to share the current knowledge on this pest and better inform its management in future.

Reasons for fast spread in Asia and the learnt lessons

Why does it spread so fast? Tuta absoluta has rapidly spread in Asia since its first detection in Turkey in 2009. It reached western and eastern India in 2014 and 2017, respectively (Sankarganesh et al. 2017). Its detection in many Asian countries has been officially reported either by the researchers in each country or by EPPO, while the presence of this pest in some countries has not been confirmed yet (see Supplementary material in Campos et al. 2017). Such a high invasion and expanding speed are comparable to the cases in Europe (Desneux et al. 2011) and Africa (Sylla et al. 2017; Biondi et al. 2018; Mansour et al. 2018). Several key reasons/drivers could explain its fast spread. First, *T. absoluta,* like other invasive alien species, has a strong intrinsic invasiveness with high reproduction potential, dispersal capacity and being able to adapt to newly invaded areas. Indeed, invasion success can only occur when the species is able to establish and sustain a population in new area as it lays the population basis allowing for further spread. The tomato pinworm is a multivoltine species with high overwintering capacity in greenhouse facilities and strong heat tolerance in open fields, which renders the pest population to sustain and increase rapidly over years (Tropea Garzia et al. 2012; Damme et al. 2015). Greenhouse facilities may not necessarily play important roles in establishment and spread of *T. absoluta* in Africa since the climate in most parts of the continent is naturally favourable for the moth based on modelling predictions (Fig. 1). In contrast, greenhouses may play important roles in sustaining and promoting its population growth and facilitate its rapid invasion in given regions. For instance, the areas that are unsuitable for overwinter success of the moth have experienced considerable damage by *T. absoluta* (the areas in blue in Fig. 1). It should be noted that those areas are covered by large areas of protected facilities (e.g. greenhouses). We hypothesize that, in some Asian countries with continental climate, greenhouse facilities may serve as a shelter for the overwintering populations because: (a) tomato and other Solanaceae crop production in winter can provide food for *T. absoluta* when there is no crop in open fields; (b) the warmer condition in greenhouses increases the chance of survival of the moth and the early arrival in the field. Second, current quarantine measures are not as effective as we have expected to prevent its dispersion within a given country and/or among geopolitical borders. Despite its danger, many Asian countries such as Turkey,

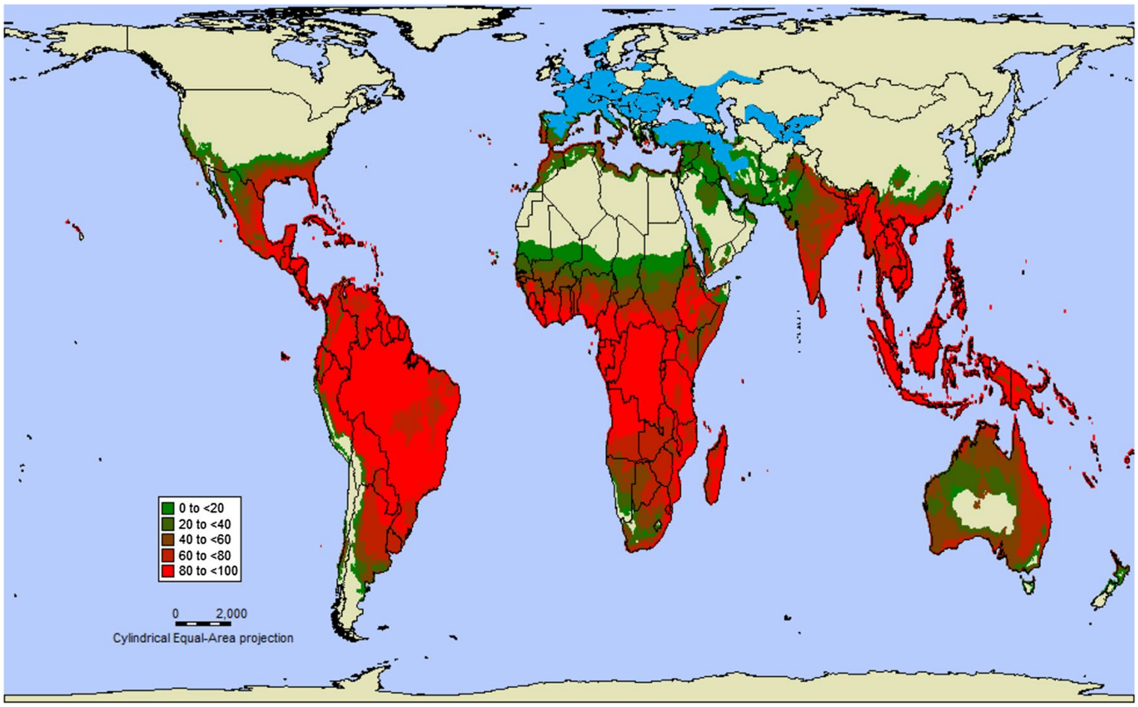

Fig. 1 Predicted distribution on Eco-climatic Index (EI) of *Tuta absoluta* throughout the world. EI values indicate the suitability of this pest (i.e. green and red regions). The blue are the invaded areas by this pest but outside of suitable areas for the moth. The higher the EI values are the more suitable climate under which *T. absoluta* could survive (Ei = 0: cannot survive, EI ~ 10: species could survive, 30: very favourable, Sutherst et al. 2007). Parameters used in CLIMEX model: moisture index: temperature index: DV0 = 8, DV1 = 20, DV2 = 30, DV3 = 42; cold Stress: TTCS = 3, THCS = −0.001, DTCS = 15, DHCS = −0.001, TTCSA = 0, THCSA = 0; heat Stress: TTHS = 42, THHS = 0.0015, DTHS = 0, DHHS = 0; dry Stress: SMDS = 0.1, HDS = −0.01; wet Stress: SMWS = 2, HWS = 0.002; day degree accumulation above DVO: DVO = 8, DV3 = 42, MTS = 7; day degree accumulation above DVCS: DVCS = 8, DV4 = 100; day degree accumulation above DVHS: DVHS = 35; degree-days per generation: PDD = 460. (Color figure online)

Israel and India have not even put this species into the quarantine list. More importantly, a combination of factors including the geographic proximity, ineffectiveness of early surveillance and weak phytosanitary efforts has favoured its spread among countries. In the United Arab Emirates, *T. absoluta* poses no danger as it is kept under supervision by the ministry (personal communications by Saji A.). However, no official quarantine and/or early warning procedures have so far been recommended in several other heavily damaged countries, such as Israel, Iran and India, to prevent its spread domestically among the provinces. Establishment of surveillance networks and actions (i.e. species identification and monitoring) at the border close to the neighbouring infested county is important to any non-invaded country. Lack of such efforts could result in untimely detection of the species, and the pest may have already spread in large areas until the damage was observed and species identified. Moreover, due to the status of bulk trade of fresh tomatoes for most Eurasia countries, it is impossible to impose strict quarantine measures on thousands of tons of fresh tomato products if importation is not banned. The cold and heat treatments are not recommended because they decrease the quality of the products. Fumigation and irradiation can be effective in controlling various instars of this pest (Cagnotti et al. 2012; Hallman et al. 2013), but they have not been implemented, maybe due to high costs and need of coordinated transnational actions. Lastly but not least important, the lack of joint-management efforts between the neighbouring invaded and non-invaded countries is another key driver for the continual invasion success. In our opinion, invasive species could be categorized as "ordinary" and "extraordinary" ones. The former usually has limited dispersal capacity and low reproduction potential. The spread process can be easily blocked if proper quarantine measures are taken across regions. However, for the extraordinary ones with high invasiveness and excellent dispersal capacity, such as *T. absoluta,* proactive efforts concerning surveillance and especially the joint management of the pest in invaded countries must be performed. In this case, non-invaded country may export effective tools to the invaded neighbouring country to help reduce the local population size, thus reducing the invasion risk.

What are the current effective efforts? Regulatory agencies in most non-invaded countries have all established surveillance protocols for early detection and quarantine, such as the USA (USDA-APHIS 2014), Australia (WTO 2009), Canada (CFIA 2017) and China (Xian et al. 2017). Eradication procedures, such as destruction of infested plants and phytosanitary practices, should be ready in case of any detection. These initiatives are expected to prevent its further expansion into new areas. In China, because fresh tomatoes, potatoes and/or solanaceous plants were seldom imported from countries of the epidemic areas, *T. absoluta* had not been a member of "The list of quarantine pests in People's Republic of China" until 2017. However, in recent years from 2014 to 2017, fresh tomato and potato as well as chilled tomato and potato are occasionally imported from Chile, Italy, France and the Netherlands (http://www.haiguan.info). Furthermore, about 40% of the pests intercepted during the custom inspections originated from tomato fruits that were imported from the countries where *T. absoluta* is present (http://www.pestchina.com). The moth has seriously occurred in the West and Southwest neighbouring countries of China, such as India, Afghanistan (Campos et al. 2017), Kyrgyzstan (Uulu et al. 2017), Kazakhstan, Tajikistan, Uzbekistan, Bangladesh and Burma (Campos et al. 2017). In view of these, *T. absoluta* has been listed in the above-mentioned quarantine list in 2018. Pakistan Agricultural Research Council (PARC) collaborating with CABI has also installed moth-capturing traps in Federally Administrated Tribal Areas (FATA) that is near to Afghanistan border (personal communications by Ali A.). A cooperative alliance among Asian countries should be established for preventing further spread of this pest.

What are the lessons that should be learnt? Nicknamed as "tomato Ebola" in Nigeria (Agbota 2017), the scientific community, the public and the stakeholders worldwide are suggested to collaborate combating this devastating pest. First, this pest should be listed as quarantine species with high risks in each Asian country without exception, as many countries have not legislated such an issue. This may be achieved through endorsement from the scientific community to each government. Second, sound quarantine order is encouraged to be shared among countries. For instance, fumigation with methyl bromide treatment had been an efficient approach in pre-clearance programmes until recently; nevertheless, its use has been banned in many countries. Thus, alternative approaches should be developed. So far, only Chile has established the pre-clearance programme (USDA-APHIS 2014). Tomato products must be packed in insect-proof cartons or containers, or covered with insect-proof mesh for export to any foreign country. Third, collaborative management of this pest including joint-applied research programme, outreach activities, demonstration of existing efficient management techniques in invaded areas, as well as organizing international workshop for this special issue are highly encouraged. As a good example, a research team from Xinjiang province (Northwest China) has already launched an intergovernmental project with one of its neighbouring countries, i.e. Tajikistan (http://www.xjkjt.gov.cn/). By exporting species-specific male annihilation and mating-disruption products from China into Tajikistan, combined with local advantage in mass-rearing and release of arthropod biocontrol agents, an integrated pest management (IPM) package is expected to be built. Such a joint action will not only benefit local agriculture in Tajikistan, but also reduce the invasion risk for China. Joint efforts with other invaded Asian countries are needed in future.

Crop damage and economic impacts

The South American tomato pinworm poses a major threat to tomato production, and relatively less to potato, eggplant and other solanaceous plant species (Biondi et al. 2018). Damage by *T. absoluta* has often been most pronounced at the beginning of its invasion into a country as local growers do not know how to cope with the pest, which was the case for Turkey in 2009 and 2010 (personal communications by Bayram Y.). Turkey, as the fourth largest country for producing tomatoes, the annual cost of chemical control of *T. absoluta*, was approximately 160.7 million Euros (Oztemiz 2014). The infestation rate of tomato fruits per plant in greenhouses reached up to 38.4% in Mersin province, and *T. absoluta* could cause 50–100% yield loss if no control measure was taken (Karut et al. 2011; Polat et al. 2016). In India, one field study has shown an infestation rate of 100% in an experimental farm in Meghalaya state (i.e. almost all the tomato plants have been heavily infested) (Sankarganesh et al. 2017). In central Asia such as Tajikistan, Uzbekistan and Kyrgyzstan, *T. absoluta* has been found abundant in tomato fields during the season and it causes high damage to the crops (i.e. up to 100%) if the pest is not properly managed (Uulu et al. 2017; Saidov et al. 2018).

Economic losses caused by *T. absoluta* are summarized as three aspects: (a) reduced production: the moth can infest tomato leaves, stems and fruits, resulting in severe yield losses (Potting et al. 2013; Galdino et al. 2015); (b) additional management costs: more chemical or non-chemical control practices have to be included in the IPM package against *T. absoluta* populations which has developed high insecticide resistance (Tropea Garzia et al. 2012; Campos et al. 2017; Biondi et al. 2018); (c) decreased and/or restricted trade: the non-infested country may ban the importation of tomato from the infested countries (Desneux et al. 2011; USDA-APHIS 2014). These reasons for economic losses are in common for invaded countries (e.g. in Europe) as well as newly invaded areas (e.g. southern Africa and central Asia). Nevertheless, in most infested countries in Asia, information on economic losses caused by the moth infestation is not available due to lack of detailed records. Rough estimations based on the data from the extension agencies and the ministries of agriculture of some countries can still be valuable. For instance, percentage of damage area has reached almost 100% in Iran, which resulted in around 10% of yield loss in both greenhouse and open-field tomatoes and loss of 35-million US dollars per year (personal communications by Sohrabi F.). The damage has decreased gradually as local farmers have started to apply various management options such as synthetic insecticides in recent years. Other factors, such as variations in production patterns (the relative growing areas of greenhouse and open-field tomatoes), climate and fluctuation of management costs (i.e. seeds, insecticides, fertilizers and other resources), make the estimation of economic losses unpredictable.

Current IPM packages: successes and failures

On a global scale, chemical control is still the primary management option in spite of its various disadvantages, such as the non-target effects on beneficial arthropods and insecticide resistance developed targeted pests (e.g. Desneux et al. 2007; Han et al. 2010; Guedes and Picanco 2012; Biondi et al. 2012, 2013; Decourtye et al. 2013; Gontijo et al. 2013; Perez-Aguilar et al. 2018; Roditakis et al. 2018). Other environmentally friendly options have been shown efficient for management of *T. absoluta*, but it is a long way ahead to promote the use of those options by growers. For instance, Zappalà et al. (2013) have reviewed the biological control of *T. absoluta* by conserving indigenous arthropod natural enemies and/or releasing commercial biocontrol agents. However, they have merely achieved success in closed and open greenhouses. Few evidence has so far been gained for practical augmentation biological control programmes in open-field tomato (Shaltiel-Harpaz et al. 2016), while other studies have merely shown the biocontrol potential of several natural enemy species (Ballal et al. 2016; Bayram et al. 2016; Salehi et al. 2016). Pheromone-based mass-trapping has been shown efficient in both protected and open-field crops (see review by Caparros Megido et al. 2013; Lobos et al. 2013). Mating disruption has been tested in greenhouses with success (Vacas et al. 2011; Cocco et al. 2013), yet this technique is relatively costly as it requires applying high doses of active substance of sex pheromone to achieve satisfactory results. The cost of mating disruption seems to be acceptable by growers in Italy (personal communication by Biondi A.), and the way they use this technique may worth being promoted to other countries. Agronomic preventative efforts mainly including sanitation practices (Desneux et al. 2010) and manipulation of irrigation and fertilization regimes are suggested to be considered for further development (Han et al. 2014, 2016a, b; Larbat et al. 2016; Dong et al. 2018; Blazhevski et al. 2018).

Current IPM components against *T. absoluta* in Asia are summarized in Table 1. Like in Europe, chemical control is the first choice for controlling the moth. However, the moth appears to show high resistance to some commonly used insecticides upon its arrival. For example, high resistance to organophosphate and pyrethroid insecticides has been reported in Iran (Zibaee et al. 2018). Fortunately, no failure of chemical control in greenhouses and open fields has so far been reported in this region. Still it does not necessarily mean that chemical control will continue to be efficient in controlling this moth in future as we have seen an increasing insecticide resistance in this moth to many chemicals more recently (Roditakis et al. 2018). Therefore, more sustainable alternative options need to be developed. The three promising options are discussed as below:

1. *Biotechnological control*: This is the second most commonly used option after insecticides, which largely bases on the use of *T. absoluta* sex pheromone. For instance, male annihilation by mass-trapping with delta traps is considered as an effective measure as it can manage low initial densities of newly arriving populations (Aksoy and Kovanci 2016; Bayram et al. 2017). However, this option may not offer satisfactory results when the moth has a high population density as even a minority of "escaped" male moths could contribute to considerable mating events.

   In practice, it requires placing a higher number of traps in crop fields to kill a high proportion of male insects from the pest population. Mating disruption has achieved success in greenhouses in Southern Europe as mentioned above, and it will have high potential to be included in future IPM programmes. In order to reduce costs, the optimization of disperser design and control of emission rate need much more efforts (Cocco et al. 2013).
2. *Biological control*: Biological control using either arthropod natural enemies or microbial products is the most studied management option so far. Similarly to the case in Europe (Desneux et al. 2010; Zappalà et al. 2013), the predator *Nesidiocoris tenuis* (Reuter) (Heteroptera: Miridae) has shown high potential in controlling the moth population in Asia. Kececi and Oztop (2017) have reported that the control efficiency of *N. tenuis* alone is comparable with its combined use with *Trichogramma evanescens* (Westwood) (Hymenoptera: Trichogrammatidae) in the greenhouses in Turkey. Moreover, Sankarganesh et al. (2017) found this predator in association with *T. absoluta* together with fortuitous parasitoids in western India. This highlights the importance of developing commercial and/or public mass-rearing of *N. tenuis* in this region. For example, this predator is mass-reared in Beijing Plant Protection Station (personal

Table 1 Summary of the current integrated pest management (IPM) components and their application status for controlling *T. absoluta* in Asia

IPM components	Specific efforts	Status	References
Chemical control	Spray of synthetic insecticides	Insecticides appear the most effective option, but the moth bears high resistance to some commonly used insecticides (e.g. abamectin, organophosphate and pyrethroid) upon its arrival	Konus (2014), Sridhar and Nitin (2016), Nozad-Bonab et al. (2017) and Zibaee et al. (2018)
Biotechnological control	Pheromone-based mass-trapping	Mass-trapping with delta traps significantly reduce the percentage of infested leaves and fruits when the moth is at low population density; it cannot save crops when the population is high. Mating-disruption products have not been commercially available in Asia	Aksoy and Kovanci (2016) and Bayram et al. (2017)
Biological control	Arthropod biocontrol agents	The indigenous predator *Nesidiocoris tenuis* has potential to control *T. absoluta* in both greenhouses and open fields in different counties. A few larval and eggs parasitoids and other Heteroptera predators were also found to inducing mortality of the moth	Ballal et al. (2016), Bayram et al. (2016), Kececi and Oztop (2017), Salehi et al. (2016), Shaltiel-Harpaz et al. (2016), Sankarganesh et al. (2017) and Varshney and Ballal (2017)
	Microbial biocontrol agents	Entomopathogenic nematodes, such as *Steinernema feltiae*, *S. carpocapsae* and *Heterorhabditis bacteriophora*, have high potential to infest and kill the larvae when they are outside their mines	Gozel and Kasap (2015), Turkoz and Kaskavalci (2016) and Kamali et al. (2018)
Agronomic control	Test of existing resistant cultivars	Some tomato cultivars show high resistance to *T. absoluta* oviposition and subsequent larval performance	Gharekhani and Salek-Ebrahimi (2014), Rostami et al. (2017), Sohrabi et al. (2016) and Ghaderi et al. (2017)
	Breeding transgenic resistant cultivars	Insecticidal transgenic crops can confer stable resistance to the moth, but it requires a rigorous and complicated risk assessment procedure	Ahmed et al. (2017) and Selale et al. (2017)
	Manipulation of soil traits (e.g. fertilizers)	Application of bio-fertilizers enhanced the control of the moth by lowering its performance and improving the biological traits of its natural enemy	Mohamadi et al. (2017a, b)
Other ecological-based control	Plant extracts such as plant essential oil and azadirachtin	Cardamom essential oil showed high toxicity to *T. absoluta* eggs, the 2nd larvae and adults; the mixture of anonin and azadirachtin is acted as efficient repellents to the moth in both greenhouses and fields	Durmusoglu et al. (2011) and Chegini and Abbasipour (2017)

communications with Hou Z.R.) to control whiteflies in tomato greenhouses (Hou Z.R., unpublished data). Thus, this predator shows high potential for inundative releases in open fields to control *T. absoluta* once it will enter China in future. In addition, a preliminary knowledge has been gained recently on other arthropod natural enemies such as the larval parasitoid *Necremnus cosmopterix* (Ribeset Bernardo) (Hymenoptera: Eulophidae) and the predator *Orius albidipennis* (Reuter) (Hemiptera: Anthocoridae) (Bayram et al. 2016; Salehi et al. 2016). Entomopathogenic nematodes have also been documented to show high efficacy for biological control of the moth, especially when the population is high. The species *Steinernema feltiae* (Filipjev) (Rhabditida: Steinernematidae) has been shown to cause high mortality in *T. absoluta* larvae, but only when the larvae were outside the mines (Gozel and Kasap 2015; Turkoz and Kaskavalci 2016), which is consistent with an earlier study in Europe by Garcia-del-Pino et al. (2013), showing that the larvae of *T. absoluta* falling from the leaves due to insecticide application could suffer severe infestation by the nematodes. Other species such as *S. carpocapsae* (Weiser) and *Heterorhabditis bacteriophora* (Poinar) (Rhabditida: Heterorhabditidae) also showed high control level against *T. absoluta* (Kamali et al. 2018).

3. *Control efficacy* via *enhanced plant resistance*: Use of inherent resistant traits or enhancement of resistance in crops is another major option for minimizing damage by pests. Much work on this aspect has been carried out to enhance the sustainable control of the moth. It is noteworthy that laboratory and field resistance evaluation of various tomato cultivars from Iran have filled the knowledge gap and paved the way for future crop breeding programmes (Table 1 "Test of existing resistant cultivars"). Leaf trichome density appears as one of the key traits that confer resistance (Sohrabi et al. 2017), but the selection on this trait needs further efforts. By investigating plant chemical compounds that mediate *T. absoluta* resistance via both antixenosis and antibiosis, a patent describing a commercial tomato cultivar resistant to the moth has been released recently (Snoeren et al. 2017). Moreover, researchers from Turkey have successfully developed insecticidal hybrid SN19 gene- and Cry1Ac gene-mediated resistance in potato and tomato, respectively, which could be promising tools for the management of the moth in future (Ahmed et al. 2017; Selale et al. 2017). Plant extracts, such as plant essential oils and azadirachtin could induce antixenosis in the moth (Durmusoglu et al. 2011; Chegini and Abbasipour 2017), can be a useful component of the IPM package. Enhanced plant resistance via manipulation of soil abiotic factors can also favour management of *T. absoluta* (e.g. bottom-up effects). Relatively low nitrogen input (not impacting plant growth) combined with optimal water input can cause negative effects on the survival and growth of the pest while not compromising the performance of its predator *Macrolophus pygmaeus* (Rambur) (Hemiptera: Miridae) (Han et al. 2014, 2015, 2016a, b). Moreover, addition of humic fertilizer and vermicompost into the soil has been shown to reduce *T. absoluta* population growth (Mohamadi et al. 2017a), but enhance the population growth of its egg parasitoid *Trichogramma brassicae* (Bezdenko) (Hymenoptera: Trichogrammatidae) (Mohamadi et al. 2017b). The mechanisms underlying this result are yet unknown, but these findings highlight the dual positive effects of using these bio-fertilizers in managing the pest.

Management failure by chemical control is predicted to appear in future. This is largely linked to the moderate or high resistance of the moth to the most commonly used broad-spectrum insecticides (Silva et al. 2011; Campos et al. 2015; Roditakis et al. 2015, 2018). Moreover, field evolution of cross-resistance to new diamide insecticide with several commonly used insecticides (e.g. chlorantraniliprole) in Brazil (Silva et al. 2016), and resistance to diamide in Italian population (Roditakis et al. 2015) will make chemical control more and more challenging. Insecticide resistance is mostly heritable, but current knowledge is insufficient to show whether the resistance level to a given class of insecticide during invasion (e.g. from Greece, Turkey, to Iran) has remained constant or increased since different classes of chemicals have been tested among the countries (Roditakis et al. 2013; Yalcin et al. 2015; Zibaee et al. 2018). Despite that, the invasion pathway of *T. absoluta* in Asia since 2009 is still unclear; we hypothesize that the populations present in central Asian counties as well as India are likely to bear high insecticide resistance. Yet no literature has so far documented such aspects. Adjacent to infested areas of central Asia counties, Xinjiang province (north-western China) being the largest open-field tomato production region worldwide is facing high invasion risk (Xian et al. 2017). Thus, insecticides should be carefully selected to control this moth once it will enter.

Promising novel management technologies

One promising direction for controlling *T. absoluta* is to breed genetically modified (GM) crops (i.e. insecticidal tomato lines). Many attempts have been made on this direction. For instance, GM *Bacillus thuringiensis* (Bt) tomato plants have been shown to confer high resistance to this moth (i.e. high mortality rate in the larvae), which suggests high potential for developing commercial resistant varieties (Selale et al. 2017). Not in tomato but targeted expression of a hybrid insecticidal gene (SN19) in potatoes can lead to 100% of mortality in *T. absoluta* as well as in Colorado potato beetle *Leptinotarsa decemlineata* (Say) (Coleoptera: Chrysomelidae) (Ahmed et al. 2017). Like other insecticidal GM crops, one should note that rigorous environmental risk assessment procedures are foreseeable if we intend to promote their wide adoption in fields (Romeis et al. 2008). However, it is worth promoting the use of GM varieties with great efforts as it will not only benefit the control of *T. absoluta* but also help optimize the IPM package as a whole. For instance, Bt cotton has been widely adopted worldwide since more than two decades. Such an adoption has not only favoured the control of the cotton bollworm *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae), but also promoted the overall biocontrol services in agro-ecosystems in China (Lu et al. 2012).

RNA interference (RNAi) is a powerful tool for gene function studies and has been proven to have great potential for insect pest control. When the sequences of double-stranded RNA, as the trigger of RNAi, match essential insect genes, silencing of these genes may result in impaired growth and/or development and even mortality of the pest. Bock (2015) provides an overview of the existing tools for plastid genome engineering and the high potential of this technology in managing agricultural insect pests. Much advances have been made for pest control by using RNAi-based gene silencing through dsRNA injection or ingestion, notably the spotted wing drosophila, *Drosophila suzukii* (Matsumura) (Diptera: Drosophilidae) (Taning et al. 2016), and the African sweet potato weevil *Cylas puncticollis* (Boheman) (Coleoptera: Brentidae) (Prentice et al. 2017). Chloroplast expression of long dsRNAs can provide crop protection from the Colorado potato beetle as a successful case study (Zhang et al. 2015). The finding in this "milestone" study has been considered to promote the development of next-generation insect-resistance plants (Zhang et al. 2017). In the case of *T. absoluta*, study by Camargo et al. (2015) has shown the potential that spraying of dsRNA formulations onto the host crops may be a useful control method. Due to cryptic nature of the larvae, tomato plants with high expression level of dsRNA will be more feasible to induce mortality in its larvae.

Sterile insect technique (SIT) is another powerful control tactic for the creation of pest-free areas or areas of low pest prevalence. This tool has been developed rapidly due to various advantages such that it is environmentally friendly, species-specific and usually compatible with other management options. Lepidopteran pests, a group that often poses major threats to crops and shows high potential to develop insecticide resistance, have been recommended to be controlled by SIT based on the area-wide IPM (AW-IPM) concept (Klassen 2005). So far there have been many successful cases of using SIT as a component to target various Lepidopteran pests (see review by Simmons et al. 2010). Unfortunately, no marked progress has been made using SIT to control *T. absoluta* except for one preliminary study (Cagnotti et al. 2012), which has shown that X-radiation at doses ≥ 350 Gy and between 200 and 250 Gy could induce malformed wings and bent legs and inherited sterility in *T. absoluta* adults, respectively. Further experiments should be designed to test the fitness and field performance of sterile males. Another bottleneck that we need to break is the low-cost mass-rearing of this species, which is the first step of SIT programmes. Recent findings have pointed out that deuterotokous parthenogenesis may compromise the efficacy of using SIT in controlling the moth (Caparros Megido et al. 2012). This issue should be further investigated to clarify whether this is an occasional case or the rate is high at the population level, and figure out whether a given percentage of individuals performing parthenogenesis will result in the control failure.

Conclusion and future outlook

The extraordinarily rapid invasion process of *T. absoluta* throughout the Afro-Eurasia appears to be underestimated before. Ineffective quarantine procedures, and lack of joint efforts in surveillance and management among the countries in Asia have facilitated its dispersion and invasion success, yet they need empirical data to be fully supported. Information asymmetry among the countries is also responsible for such a consequence. Some countries even did not realize the economical and ecological importance of this pest as it has so far not been included in their quarantine lists. Upon its arrival, many alternative management options have been available, but local growers usually rely heavily on insecticides, which harms local agro-ecosystems and food safety.

Future priorities should at least be given to two aspects. First, existing control options need further tests and validation by more extension programmes. The successful ones shown in a given agro-ecosystem are suggested to be demonstrated and shared across the region. In the meanwhile, we need more financial inputs for optimization and application of those emerging promising technologies as mentioned above. Second, due to the high invasion capacity of *T. absoluta*, a cross-regional network (for example called "Tuta-Web") is proposed to be built by gathering the researchers, policy-makers and major stakeholders from all the Asian countries as well as the members from un-infested areas. Besides implementing outreach activities in each country, international workshops of *T. absoluta* ecology and management are suggested to be organized regularly to promote communication and collaboration among the partners. In the new era, especially in the context of "the Belt and Road initiatives", the human exchange, transportation and international trade are facing an unprecedented increase, which makes the surveillance and control of invasive alien species more challenging; therefore, joint effort is the only key to reducing biohazard of *T. absoluta* in infested areas, and preventing or delaying its ongoing invasion journey to new areas, so do the other invasive alien species.

Author contributions

PH, SW, AB and ND conceived the manuscript. PH wrote the manuscript. ZZL conducted the modelling work. All authors provided materials for the writing. All authors read and approved the manuscript.

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Compliance with ethical standards

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Conflict of interest All authors declare that they have no conflict of interest.

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