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Case Study

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Sustainable Management of the Invasive *Tuta absoluta* (Lepidoptera: Gelechiidae): an Overview of Case Studies From Latin American Countries Participating in Plantwise

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Abstract

Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae) is indigenous to South America. It has invaded several tomato-producing regions worldwide resulting from globalization of commerce and trade. *T. absoluta* is now considered one of the most devastating pests affecting tomato plants and fresh tomatoes. Although tomatoes are the primary host, *T. absoluta* can feed and develop on other solanaceous plants as well as plants from other botanical families, including 15 economically important crop species and weeds. Chemical control continues to be the primary management option, even in areas where *T. absoluta* is an invasive species. This occurs despite the well-documented effects of chemical insecticides on the environment and its low efficacy. In this article, we discuss the biology, ecology, and a more sustainable management for *T. absoluta*. The management plan includes periodic monitoring program to improve pest management strategies by detecting the presence or arrival of the pest in a given host plant, estimating population levels over time, and studying the distribution of the pest. Lastly, we discuss pest management from the perspective of Plantwise, an innovative global program which aims to contribute to increased food security, based on its implementation in Bolivia and Costa Rica. In both countries, plant clinics have been established to show farmers new ways of managing pests in a sustainable way while maintaining crop productivity. The implementation of the Plantwise program resulted in a reduction in pesticide use via incorporation of less toxic active ingredients and sustainable pest management strategies such as biological control. Plantwise has encouraged the use of cultural end ethological practices by smallholder farmers in participating countries.

Key words: pest management, Plantwise, sustainable strategy

Resumen

Tuta absoluta (Meyrick) (Lepidoptera: Gelechidae) es originaria de Sudamérica. Esta ha invadido varias regiones productoras de tomate a nivel mundial como resultado de la comercialización y globalización. *T. absoluta* actualmente es considerada una de las plagas más devastadoras que afectan plantas de tomate y los frutos frescos. Aunque el tomate es el principal hospedante, *T. absoluta* puede alimentarse y desarrollarse en otras solanáceas, así como de otras familias botánicas, incluidos 15 cultivos de importancia económica y malezas. A pesar de los efectos del control químico sobre el ambiente y la salud pública y su baja eficacia, este sigue siendo la principal opción de manejo, incluso en áreas donde *T. absoluta* se considera una especie invasora. En este artículo, se discute sobre la biología y ecología de la especie, así como las estrategias de manejo más sustentables para *T. absoluta*, que incluye un programa de monitoreo constante como estrategia de manejo de plagas mediante la detección de la presencia o llegada de la plaga en una planta hospedante determinada, la estimación de los niveles poblacionales a lo largo del tiempo y el estudio de la distribución de la plaga. Se discute el manejo de plagas desde la perspectiva de Plantwise, un programa global innovador que tiene como objetivo contribuir a reforzar la seguridad alimentaria, con base en su implementación en Bolivia y Costa Rica. En ambos países se han establecido clínicas de plantas

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para mostrar a los agricultores nuevas formas de manejar las plagas de manera sostenible mientras se mantiene la productividad de los cultivos. La implementación del programa Plantwise resultó en una reducción en el uso de pesticidas mediante la incorporación de ingredientes activos menos tóxicos y estrategias de manejo sostenible de plagas, como el control biológico. Plantwise también ha fomentado el uso de prácticas culturales y etológicas por parte de los pequeños agricultores en los países donde el programa ha sido implementado.

Palabras clave: Manejo de plagas, Plantwise, estrategias sostenibles

Tuta absoluta (Meyrick) is one of the most devastating pests affecting tomato plants and fresh tomatoes (*Solanum lycopersicum* L., Solanaceae). This lepidopteran species causes high levels of crop production loss, especially when no control strategies are implemented (Sylla et al. 2017, Mansour et al. 2018). *T*. absoluta is indigenous to South America, but has invaded production areas in Europe, Asia, and Africa. The expanding distribution of this pest is the result of globalization which, along with other factors, is considered responsible for the increase in invasive species (El-Shafie 2020). Molecular evidence suggests that it was probably introduced to Europe from central Chile (Rwomushana et al. 2019).

The economic importance of *T. absoluta* has led to management strategies being focused on pesticides (Illakwahhi and Srivastava 2017). These include chemicals with a wide range of organic micropollutants that negatively impact the environment, mostly due to biomagnification and bioconcentration (Hassaan and El Nemr 2020). Additionally, most pesticides pose risks to humans ranging from contact poisoning and inhalation to serious health problems, such as severe hematologic morbidity and lung dysfunction, immune system deficiencies, congenital deformities, and various types of cancer (Hassaan and El Nemr 2020, Maksymiv 2015). The excessive use of synthetic insecticides can also lead to environment-wide problems, such as insecticide-resistant pests (Guedes 2017), pest resurgence (Kumar et al. 2021), the reduction of natural enemies (Torres and Bueno 2018), and insecticide residue on harvested crops (Ahmed et al. 2011, Neme and Satheesh 2016). Thus, more sustainable strategies are being used alongside chemical control, such as Integrated Pest Management, including biological control agents such as parasitoids, predators, and entomopathogenic microorganisms; botanical insecticides; and pheromones and plant resistance (Erol et al. 2021, Mohamed Mahmoud et al. 2021, Saeidi and Raeesi 2021, Ünlü et al. 2021).

Agricultural pest management decision-making should be informed by sampling and monitoring that guide users in assessing the need for a proper tactic. As of this writing, decision-making systems are still under development for implementation involving *T. absoluta*; however, even these incipient systems could facilitate the scheduling of agricultural practices according to rough estimates of economic thresholds, as well as farmers' intuition and experience. They could also help overcome market uncertainty and any personal aversion to risk (Rincón et al. 2021).

Host Plant Range, Feeding Damage, and Impact

Tomatoes have been reported as the primary host of *T. absoluta*; however, this pest can feed and develop on other Solanaceae plants, such as potatoes (*Solanum tuberosum* L.), eggplants (*Solanum melongena* L.), and tobacco (*Nicotiana tabacum* L.) (Caparros Megido et al. 2013, Pereyra and Sánchez 2006, Rwomushana et al. 2019). Portakaldali et al. (2013) recorded other host solanaceous species, including sweet peppers (*Capsicum annuum* L.), sweet cucumber (*Solanum muricatum* Aiton), and several other solanaceous and nonsolanaceous weeds, including black nightshade (*Solanum nigrum* L.), field bindweed (Convolvulaceae: *Convolvulus arvensis* L.) and lambsquarters (Amaranthaceae: *Chenopodium album* L.).

More recently, Cherif and Verheggen (2019) compiled a list of plant species harboring *T. absoluta*, which included 44 species from nine botanical families and 15 species of economically important crops, with miscellaneous species classified as spontaneous weeds in both cases. However, according to our more recent review, 52 plant species have now been reported as hosts (Table 1).

Though several new plant species have been identified as hosts following *T. absoluta*'s arrival in Europe, Africa, and Asia, Bawin et al. (2015) suggested that *Solanum* species could be more suitable as host plants (Fig. 1A and B).

T. absoluta can also use other solanaceous plant species for oviposition, which allowed it to spread across northern Europe and all other areas of colonization. This suggests that it uses a wide variety of host plants from different botanical families to ensure its survival throughout the year, even in the absence of tomato crops (Mohamed et al. 2015). Cherif and Verheggen (2019) recorded 44 plant species for *T. absoluta*, but the pest has only completed its life cycle on 11 (25% of the plants), all of which were from the Solanaceae family, while partial life cycles, observed oviposition or no oviposition were reported on 6.8, 6.8, and 18.2%, respectively. Information is still lacking for the majority of the plant species (19 spp.) on the list (Fig. 2).

Studies in chemical ecology have demonstrated that volatile organic compounds (VOCs), consisting mainly of terpenoids in tomato leaves, are responsible for attracting *T. absoluta* females to oviposit on solanaceous species. VOCs have been also detected in potatoes and other *Solanum* species, which could explain why *T. absoluta* develops on these host plants (Proffit et al. 2011, Caparros Megido et al. 2013).

Feeding damage on host plants is caused by larvae, which penetrate the leaves to feed on the mesophyll (Bogorni et al. 2003). This results in irregular mines, which negatively affect photosynthetic rate and can cause up to 100% of yield losses in tomato crop production (Shiberu and Getu 2017). In a greenhouse experiment, Cely et al. (2010) demonstrated that biomass, quality, and number of fruits were seriously affected when there were more than two *T. absoluta* female moths per tomato plant. Fruit damage (45–100%), leaf area consumption (27–43%), and apical leaf defoliation were observed in plants infested with 6–10 female moths. Denser populations of *T. absoluta* were associated with decreases in plant height, number of internodes, number of leaves and leaflets, and the number and biomass of fruits.

For several years, *T. absoluta* was restricted to South America; thus, only 3.1% of cultivated regions and 5% of tomato crops worldwide were affected. However, following its introduction to several European, African, and Asian countries since 2006, 2008, and 2009, respectively, both tomato cultivation and outbreaks of

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Table 1. Cultivated and noncultivated plant species hosting *T. absoluta* worldwide

Family	Species	References
Crop species		
Solanaceae	*Solanum lycopersicum* L.; *Solanum melongena* L.; *Solanum muricatum* Ait.; *Solanum tuberosum* L.; *Capsicum annuum* L.; *Nicotiana rustica* L.; *Nicotiana tabacum* L.; *Physalis peruviana* L.	Pereyra and Sánchez 2006, Proffit et al. 2011, Portakaldali et al. 2013, Bawin et al. 2015, Mohamed et al. 2015, Cherif and Verheggen 2019, Idriss et al. 2020
Amaranthaceae	*Beta vulgaris* L. var. vulgaris; *Spinacia oleracea* L.	
Cucurbitaceae	*Citrullus lunatus* Schard; *Cucurbita pepo* L.	
Fabaceae	*Medicago sativa* L.; *Phaseolus vulgaris* L.; *Vicia faba* L.	
Noncrop Species		
Solanaceae	*Atropa belladonna* L.; *Datura ferox* L.; *Datura stramonium* L.; *Lycium chilense* Miers.ex Bertero; *Lycium halimifolium* Mill.; *Lycopersicon puberulum* Phil.; *Nicandra physalodes* L.; *Nicotiana glauca* Graham; *Physalis viscosa* L.; *Salpichroa origanifolia*(Lam.) Baill.; *Solanum bonariense* L.; *Solanum dubium* Fresen; *Solanum dulcamara* L.; *Solanum elaeagnifolium* cav.; *Solanum habrochaites*S. Knapp & D.M.Spooner; *Solanumlyratum* Thunb.; *Solanum nigrum* L.; *Solanum sisymbriifolium* Lam.	
Amaranthaceae	*Amaranthus spinosus* L.; *Chenopodium album* L.; *Chenopodium bonus-henricus* L.; *Chenopodium rubrum* L.;	
Asteraceae	*Xanthium brasilicum* Vell.; *Xanthium strumarium* L.	
Convolvulaceae	*Calystegia sepium* L.; *Convolvulus arvensis* L.	
Euphorbiaceae	*Jatropha curcas* L.	
Geraniaceae	*Geranium robertianum* L.	
Malvaceae	*Malva sylvestris* L.	

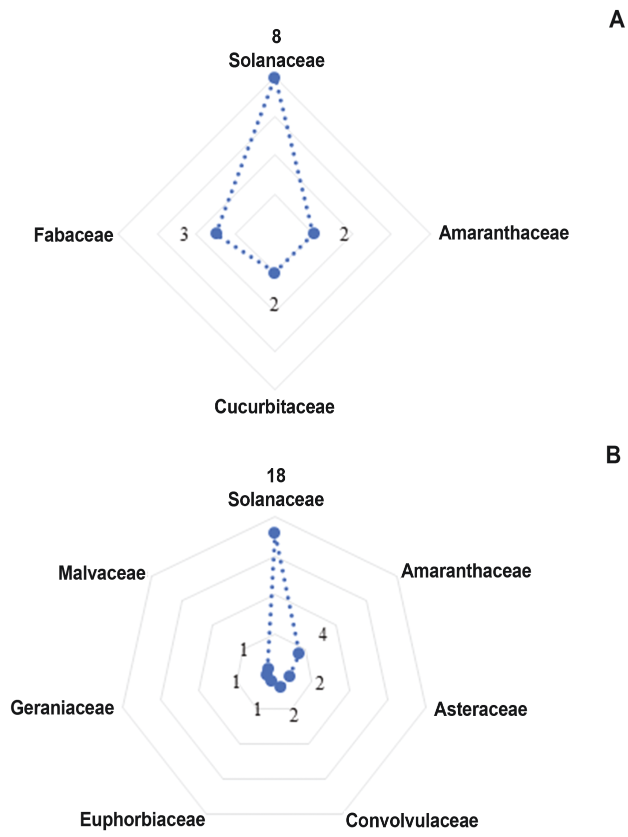

Fig. 1. *T. absoluta* host plant associations: cultivated (A) and noncultivated plant species (B).

T. absoluta sharply increased in most productive regions. Thus, a vast area of cultivated lands worldwide is currently threatened by this pest (Desneux et al. 2011).

Origins and Current Geographic Distribution

The origins of *T. absoluta* are controversial, and two hypotheses have been developed. Central America was initially postulated as the center of origin; however, records have been uncertain until recently, and *T. absoluta* has not been reported in this area for almost`50 yr (Desneux et al. 2011). More recent research suggests that the Peruvian central highlands are the center of origin (Biondi et al. 2018).

In the early 1980s, *T. absoluta* was reported in several Latin American countries, including Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Uruguay, and Venezuela, where it develops under both open-field and greenhouse conditions from 1,000 to 3,500 m above sea level (Fig. 3) (Desneux et al. 2010, EPPO 2022).

T. absoluta was restricted to the Americas for several years, but was introduced to other continents in late 2006, probably as a result of the export plants and fruits from South America (Campos et al. 2017, Esenali Uulu et al. 2017). It rapidly spread across tomato fields in the Mediterranean Basin, Europe, Asia, and north, west, and central Africa. It is currently threatening production areas in Asia, mainly in China and India, the two leading tomato producers worldwide (Esenali Uulu et al. 2017, Verheggen and Fontus 2019).

Following the initial invasion, *T. absoluta* has been reported in several countries. In 2016, it was reported in 14 out of 17 locations surveyed in Nepal, where the number of infested plants varied from

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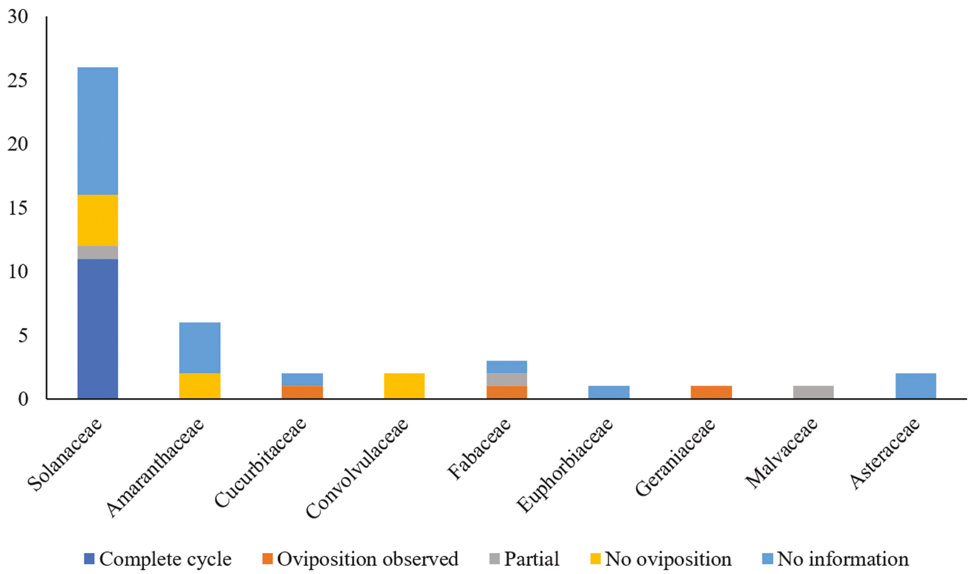

Fig. 2. Percentage of plants suitable for the development of *T. absoluta*.

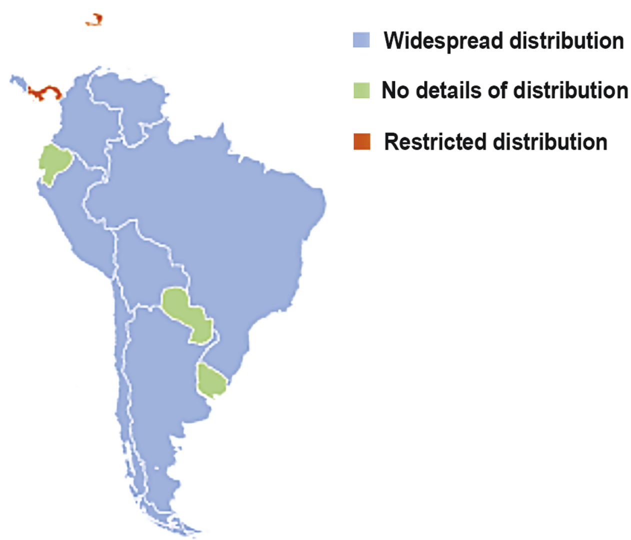

Fig. 3. Geographic distribution of *T. absoluta* in the Americas (data from EPPO 2022).

<25% to 76–100% across all of the major tomato-growing areas in Kathmandu, Lalitpur, Bhaktapur, and Kavrepalanchowk (Bajracharya et al. 2018). Though Nepali tomatoes are cultivated mainly for domestic purposes, the damage inflicted by *T. absoluta* would result in crop losses of about 25%, accounting for US$19.7M. A more comprehensive economic impact analysis shows a social welfare loss of US$22.4M and a price increase of 32% (Venkatramanan et al. 2020).

In November 2015, low to moderate levels of *T. absoluta* were recorded on tomato leaves, flower buds, apical shoots, and fruits in the sub-temperate mid-hills of Himachal Pradesh, India, which constituted a new distribution record for this particular pest in the Northwestern Himalayan region (Sharma and Gavkare 2017). In February 2017, *T. absoluta* was found in Kyrgyzstan, Central Asia, occurring in greenhouses where tomatoes were being raised. Infestation levels reached <10% in the field, but were dramatically higher (90–95%) in greenhouses (Esenali Uulu et al. 2017).

In southern Africa, Mutamiswa et al. (2017) reported that *T. absoluta* has been detected in Botswana. Local markets import tomato fruits and seedlings from Zambia and South Africa, where the pest was first recorded in May and September 2016, respectively. According to the authors, *T. absoluta* was originally found in only two Botswanan districts; however, there is a high chance that it will rapidly spread to other districts, as the local ecological and climatic conditions are similar to those of South America.

In Central America and the Caribbean, *T. absoluta* is frequently detected. In the middle of 2018, it was first recorded in four tomato fields in the Department of Sud (Haiti), where growers reported unprecedented outbreaks. These resulted, on the one hand, in larger, more frequent doses of insecticide, which in turn accelerated the development of insecticide-resistant pests, and, on the other hand, in *T. absoluta*'s rapid expansion to the Dominican Republic and other Caribbean countries (Verheggen and Fontus 2019).

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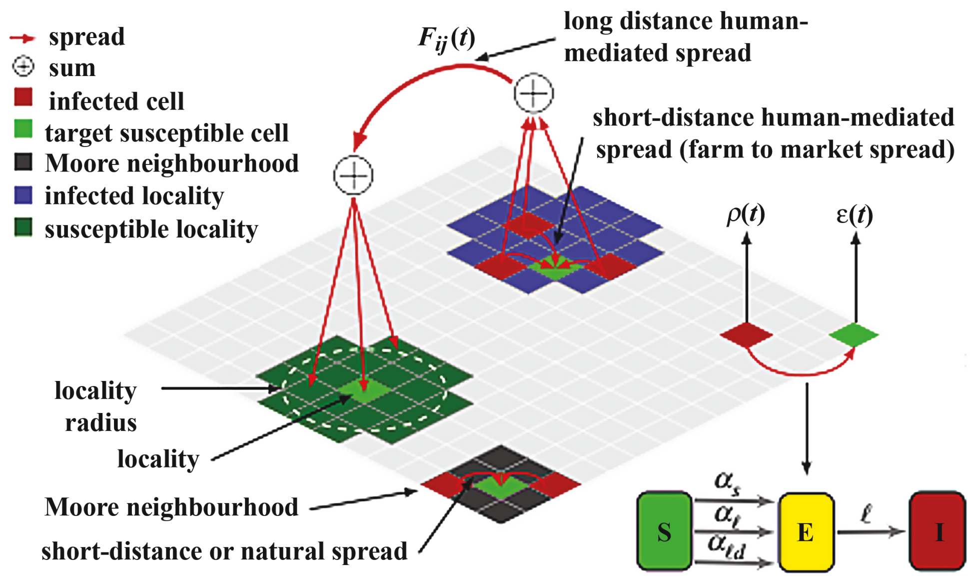

Fig. 4. Multi-pathway model concept developed by McNitt et al. (2019) to describe the spread of *T. absoluta* (From McNitt et al. 2019).

Globalization and world trade have increased the threat to global agriculture since these pests cause crop loss and adversely affect food security, though the magnitude and distribution of the pests can vary between countries and regions (Paini et al. 2016).

McNitt et al. (2019) described two distinct spread patterns primarily determined by the parameters of the paths taken by invasive pests. The first is characterized by the absence of either long-distance, human-mediated spread or brisk spread between geographically adjacent cells, driven by a latency period. In the second model, long-distance pathways play a significant role, and there is relatively slow spread between geographically adjacent cells (Fig. 4).

Analysis of historical invasion records suggests that even with modest, self-mediated spreading capabilities, *T. absoluta* can quickly expand its geographic range through domestic city-to-city vegetable trade. Thus, it is expected that, in the coming years, this pest could invade all major vegetable-growing regions in continental Southeast Asia (McNitt et al. 2019).

On the other hand, climate change greatly affects the abundance and geographical distribution of invasive species whose eurythermal conditions allow them to maintain physiological functionality across varying climates (Hulme 2017). Tarusikirwa et al. (2020) investigated the short- and long-term adaptive responses of *T. absoluta* fourth instar larva and adults by measuring their temperature tolerance traits, such as their critical thermal (CT) limits, heat knockdown time (HKDT), chill coma recovery time (CCRT) and supercooling points (SCP). The authors showed that rapid cold hardening (RCH) improved CTmin and HKDT in larvae, but impaired SCP and CCRT; meanwhile, heat hardening impaired CT, CCRT, and SCP but not HKDT, demonstrating that larvae can shift their thermal tolerance over both short and long periods of time, which assists them in adapting to new environments.

Biology

The *T. absoluta* life cycle takes place over five stages: egg, larva, pupa, prepupa, and adult. Each stage is directly related to the species of the host plant and environmental factors, such as temperature (Vélez 1997).

Eggs

Eggs are elliptical in shape (0.33 × 0.22 mm) and individually deposited on the undersides of the leaves, although they can be found anywhere on the plant, with an elliptical shape and creamy white to bright yellow color (El-Shafie 2020). They have a mean incubation time of four to eight days, depending on climate; however, incubation time widely varies according to different factors (Ramírez et al. 2010). Nayana and Kalleshwaraswamy (2015) reported an incubation time of 3.9 d at 25°C in India, but variations can occur depending on temperature and relative humidity (RH), as reported by Shiberu and Getu (2017) who found that incubation time varied from 10 to 10.5 d at 32°C and 40% RH, or up to 13 to 13.5 d at 20.5°C and 55% RH. Silva et al. (2015) also observed variations caused by rearing substrate, and found that incubation time varied from 3.9 to 4.08 d in two tomato lines (Bravo and Tex 317) in Brazil.

Larvae

Per Silva et al. (2015), *T. absoluta* goes through four larval instars with a mean larval development time ranging from 8.91 to 9.87 d at constant (25°C) and at alternating temperature (30/20°C), respectively. The authors stated that the first instar was significantly longer (3.20 d) at alternating than at a constant temperature (2.0 d on cultivar Bravo and 2.4 d on cultivar Tex 317), while the third instar was significantly shorter on Bravo at 25°C compared to other tomato lines and temperature settings. Conversely, no significant differences were observed in the development of the second to fourth instars. Nayana and Kalleshwaraswamy (2015) reported a slightly longer development period (11.8 d at 25°C), with the instars lasting 3.25, 2.35, 2.45, and 3.89 d from the first to fourth instars, respectively. Since similar temperatures were used in both studies, these differences could be attributed to the plant materials used.

The first instar larva is white in color with a dark brown head, cylindrical to lightly dorsoventrally flattened, and with five pairs of prolegs (Vargas 1970). It penetrates the epidermis of the leaf to feed on the mesophyll, producing mines (Fernández and Montagne 1990). Larvae are also able to feed on buds, flowers, or fruits, but prefer newly emerged leaves and flower clusters, which may result in the loss of a complete cluster (López 1991). Second instar larvae are similar in shape to first instar larvae, reaching a length of 2.8 mm.

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Fig. 5. Larval instars of *T. absoluta.*

Third instar larvae are initially whitish-gray, later turning green and finally white, and grow to about 4.7 mm in length (Vargas 1970). During the fourth instar, larvae are about 7.7 mm in length and show a dorsal red spot extending from the ocelli to the posterior margin (González 1989). Fourth instar larvae prefer to penetrate fruits at the pedicel end, creating tunnels that result in fruit deformations and facilitate the entrance of pathogens that can cause rotting, ultimately rendering the fruits commercially useless (Fig. 5) (Apablaza 1992).

Pupae

Obtect (legs and wings can be differentiated) and cylindrical (length = 4.35 mm, 1.1 mm diameter), the pupae are initially green, later turning dark brown, and are mostly covered with white and silky cocoons (Vargas 1970, Apablaza 1992). The pupa stage normally lasts 8 to 15 d (Vélez 1997). Studies have shown great variation in pupa development time, ranging from 9.15 d at 25°C (Nayana and Kalleshwaraswamy 2015) to 8.2 d at 20.5°C and 55% RH to 8.6 d at 32°C and 40% RH (Shiberu and Getu 2017). Silva et al. (2015) proved that differences between the development times of female and male pupae could be attributed to the effects of temperature and tomato cultivar: pupae that produced female adults lasted 6 d in cultivar Tex 317 at 25°C and 7.57 d in cultivar Bravo at 30/20°C, while pupae that produced male adults lasted 6.14–7.85 d under the same conditions as the female pupae.

Adults

Adults are about 6 mm long, with a wingspan ranging from 9 to 13 mm in females and 8.5–12 mm in males. Wings are narrow and dark gray in color, with light brown and cream scales. Adults have a mean oviposition period of about 4 d, mean longevity is 8.6 d, and the ratio of females to males is 1–3 with a fecundity of 52 eggs per female (Vélez 1997).

Strategies of Control

Chemical Control

Chemical control remains the primary management option to control *T. absoluta* (Roditakis et al. 2018, Han et al. 2019); this is despite its well-documented effects on the environment and public health, as well as reduced efficacy to manage this pest (Illakwahhi and Srivastava 2017). *T. absoluta* was initially controlled using organophosphates (OPs); these were gradually replaced by pyrethroids and, more recently a broader suite of chemicals including abamectin, acylurea, insect growth regulators, tenbufenozide, and chlorfenapyr were introduced in the 1990s (Lietti et al. 2005).

Field studies were conducted in 2001 and 2005 in Brazil to determine the efficacy of spinosad, emamectin, and indoxacarb in controlling *T. absoluta*, and the impact of this control on the occurrence of other pests in pole tomatoes. Spinosad + adjuvant (Break Thru) was determined to be the best treatment. The study documented the importance of combining adjuvants with insecticides for pest control (Dos Santos et al. 2011). A survey to assess the efficacy of several chemical molecules in Loitokitok (Kenya) demonstrated that, although chlorantraniliprole, flubendiamide, profenofos, spinetoram, emamectin, and lambda-cyhalothrin are commonly used, 51.7% of growers prefer chlorantraniliprole due to its ability to control several lepidopteran pest species, including *T. absoluta* (Ndalo et al. 2015). A four-year survey was conducted with 35 groups across Greece, Italy, Spain, Israel, and the UK between 2012 and 2016 to evaluate *T. absoluta*'s response to chlorantraniliprole, indoxacarb, emamectin benzoate, and spinosad, ultimately indicating six cases of low/moderate resistance to the emamectin benzoate (resistance ratio [RR]: 15-fold); a single case of resistance to spinosad (RR: 33-fold); and five cases of resistance to indoxacarb (RR: 13–91-fold) (Roditakis et al. 2018). After 2015, resistance to chlorantraniliprole was widespread in Italy and Greece (RR: 64-fold) and in Israel (RR: 22,573-fold), but not in the UK or Spain. The absence of diamide resistance in tomato leaf miner populations in Spain is most likely due to a recently established integrated pest management (IPM) program including nonchemical measures and the rotational use of insecticides with different modes of action, such as diamides, avermectins, the spinosyns and the oxadiazines (Roditakis et al. 2018).

Chemical pesticides remain an important component of IPM since they are considered as the first line of defense, providing a quick fix to pest pressure (Tarusikirwa et al. 2020). However, it is necessary to alternate active ingredients and different modes of action (Braham and Hajji 2012). Insecticide can be a component of a sustainable, integrated pest management program if used correctly and with a combination of pest management tactics. Although it is true that overapplication of insecticide can lead to resistant populations, all insecticide use is not in excess (Roditakis et al. 2018).

Because farmers often use insecticides with the same ingredients or effects, pest resistance is commonly observed in agroecosystems. Pesticide rotation schedules, which consist of alternating use of pesticides with dissimilar modes of action, can help slow down this phenomenon, particularly if cross-resistance mechanisms cannot be identified (Cloyd 2010). Per Cloyd (2010), the population of individual pests resistant to one pesticide will decline when a pesticide

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with a different mode of action is applied, and those individuals may be less fit than nonresistant individuals, depending on the number of generations produced. In addition to pesticide rotation, the use of insect growth regulators insecticides and, more recently, novel chemical molecules such as spinetoram, cyantraniliprole, flubendiamide, and spinosad, has taken the place of such insecticides as organophosphates, pyrethroids, cartap, and abamectin, thereby diminishing their effects on the environment (Rwomushana et al. 2019).

Biological Control

The success of an invasive species depends on its life history, ability to adapt to different climates, competition with native species, and the impact of natural enemies on the pest population. The latter is crucial in terms of distribution and abundance, and could be related to the absence or low efficacy of natural control in the new territory, as stated by the enemy release hypothesis (Zappalà et al. 2013).

Several natural enemy species are capable of controlling *T. absoluta* population levels. Hemipteran mirids have been observed to be the most promising biocontrol agents against this pest. In Brazil, studies on biology and the predation capacity of heteropteran generalist predators indicated that three zoophytophagous mirid predators—*Campyloneuropsis infumatus* (Carvalho) (Hemiptera: Miridae), *Engytatus varians* (Distant) (Hemiptera: Miridae), and *Macrolophus basicornis* (Stål) (Hemiptera: Miridae)—might be good candidates for *T. absoluta* control, owing to their ease establishment in tomato fields, high predation rate, and limited damage to tomato plants and fruits (Bueno et al. 2012, Silva et al. 2016, Illakwahhi and Srivastava 2017, van Lenteren et al. 2017).

Over the last few years, 15 arthropod species have been found to prey on *T. absoluta* in Western Palearctic countries. These species mostly belong to the hemipteran families Miridae, Anthocoridae, Nabidae, but also in Chrysopidae (Neuroptera), Formicidae (Hymenoptera), and there are also two Phytoseiidae mites (Zappalà et al. 2013).

Egg and larva parasitoids, such as *Trichogramma pretiosum* (Riley) (Hymenoptera: Trichogrammatidae) and *Apanteles* sp. (Hymenoptera: Braconidae), have also been used to manage *T. absoluta*. *T. pretiosum* has been successfully used in Brazilian biological control programs for tomato moths since the 1990s (Michereff Filho et al. 2013). Since 2013, mainly after *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae) caused significant yield losses, *T. pretiosum* has been officially registered for use in Brazil. Today, there are nine different commercial products that use this egg parasitoid to manage *T. absoluta*. The standard usage recommendation is 450,000 *T. pretiosum* adults divided into 30 points per hectare. Releases must start 15–20 d after tomato transplantation or 20–30 d, in the case of direct seeding, and last for at least twelve weeks. Complementary management strategies, such as crop rotation, destruction, incorporation of crop residues immediately after tomato harvests, and the use of cultivars more adapted to the region, are strongly recommended.

Trichogrammatoidea bactrae Nagaraja (Hymenoptera: Trichogrammatidae) in Argentina and *Trichogramma cacoeciae* Marchal (Hymenoptera: Trichogrammatidae) in Colombia have shown egg parasitism rates higher than 70% (Riquielme Virgala and Botto 2010, López 2013). In the case of larval parasitoids, *Apanteles gelechiidivoris* Marsh (Hymenoptera: Braconidae) prefers third instar *T. absoluta* larvae, resulting in a mortality rate higher than 70% (Morales et al. 2013). Other larval parasitoids attack third and fourth instar mature caterpillars, especially the braconid species *Bracon* sp., *Earinus* sp., and *Conura* sp. Bajonero et al. (2008) evaluated the reproductive capacity of *A. gelechiidivoris* given different host densities (5–160 larvae) under four thermal settings (14, 20, 26, and 32°C). Their study showed that the life cycle varied from 39 d at 14°C to 17 d at 32°C, while longevity varied from 7.5 d at 14°C to 2.4 d at 32°C. Similarly, Miranda et al. (1998) observed that the first and second larval instars are the most critical in biological control programs because they are the most susceptible to parasitism. According to the authors, their natural predators are *Xylocoris* sp. (Heteroptera: Anthocoridae), *Cycloneda sanguinea* (L.) (Coleoptera: Coccinellidae), and members of the Phlaeothripidae (Thysanoptera) family, which constitute the key mortality factor as they account for 79.4% of larval mortality. Conversely, parasitism by *T. pretiosum* (Riley) (Hymenoptera: Trichogrammatidae) produced low egg mortality levels (8.6%), while *Goniozus nigrifemur* Ashmead (Hymenoptera: Bethylidae) produced very low levels of larval parasitism (0.1%).

Natural products derived from fungi, particularly endophytes, represent an important control method for crop pests; thus, endophytic fungi are seen as promising alternatives to pesticides in sustainable and organic farming systems (Mohamed Mahmoud et al. 2021). Formulations based on entomopathogenic fungi containing *Beauveria bassiana* (Balsamo) Vuill. (Hypocreales: Clavicipitaceae) or the bacteria, *Bacillus thuringiensis* var. *kurstaki* (Berliner) (Bacillales: Bacillaceae) have shown a high level of insecticidal efficacy on all larval stages of *T. absoluta,* particularly on the first larval instars, and are available in several countries worldwide (Harizia et al. 2019, Saranraj and Jayaprakash 2017).

Despite the importance of biological control in the management of agricultural pests, some factors have limited its advance. In the case of classical (introduction) or inundative biological control, insects (predators or parasitoids) must be reared on a smaller scale (inoculative releases) or larger scale (mass rearing) targeted to inundative releases (Parra 2010). However, in Latin America, there are few officially registered biocontrol agents, which limits their commercialization; additionally, more rigorous quality control programs need to be implemented during the production phase, and it is also necessary to increase the number of registered companies that produce microbial control agents, predators and parasitoids in Latin American countries (Kondo et al. 2020). In Costa Rica, for instance, the National Program for Organic Agriculture (Programa Nacional de Agricultura Orgánica [PNAO]) created a program to promote the use of microbiological agents in pest control; however, this program was only moderately successful because some of the farmers started marketing entomopathogens without knowing what type of fungus they were selling. Due to a lack of quality control, the pathogens were not registered with the Ministry of Agriculture and Livestock (MAG), and production was stopped (Blanco-Metzler and Morera-Montoya 2020). Similarly, in 2020, the Department of Agriculture, Livestock and Food Supply (MAPA) in Brazil launched the National Bio-inputs Plan ('*Plano Nacional de Bioinsumos*') with the purpose of leveraging Brazilian biodiversity to encourage the use of biological control and other natural biological compounds. In general, Brazil has increased its use of biological control by an average of 15% a year, which is higher than the international average.

Mohamed Mahmoud et al. (2021) demonstrated that *B. bassiana* and *Clonostachys* spp. (Hypocreales: Bionectriaceae) are effective against *T. absoluta* larvae. This is the first report to document *Clonostachys* spp.'s pathogenic abilities against *T. absoluta*. *Metarhizium anisopliae* (Metsch.) Sorokīn (Hypocreales: Clavicipitaceae), *Verticillium lecanii* (Zimm.) Viegas (Hypocreales: Cordycipitaceae), and *B. bassiana*, are also effective against second instar *T. absoluta* larvae, achieving the highest mortality rates seven days after application (87, 57, and 66%, respectively) (Erol et al. 2021).

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Saeidi and Raeesi (2021) demonstrated that the integration of two environmentally favorable methods (host plant resistance and biological control) was effective in sustainably managing *T. absoluta* under greenhouse conditions. Their experiment consisted of infesting both susceptible and resistant tomato cultivars with *T. absoluta* during the first-flowering stage and releasing *Trichogramma brassicae* Bezdenko (Hymenoptera: Trichogrammatidae) ten days later. The combination of resistant cultivars and biological control resulted in significant reductions in the number of infested leaves, number of larvae per plant, number of mines per leaf, and number of infested fruits per plant. Similarly, Buragohain et al. (2021) revealed that the implementation of an IPM package including microbial pesticides (*B. thuringiensis* var *kurstaki*, *B. bassiana*), neem products, and chlorantraniliprole in step with the farmers' usual practice (i.e., calendar-based application of chemical pesticides) significantly reduced *T. absoluta* infestations without any compromise in the marketable yield (around 25 and 22 ton/ha), even reducing crop protection costs (50%). Therefore, IPM packages can be an effective, economical tool in managing *T. absoluta* infestations on tomato plants. Giorgini et al. (2019) claimed that the best approach to controlling invasive pests is the adoption of IPM. In the case of *T. absoluta*, the integration of biological control agents (e.g., mirid predators and egg parasitoids), microbial insecticides, selective chemical insecticides, and sex pheromone-based control seems to be promising. Nonetheless, future challenges include the development of pest-resistant tomato cultivars, the management of wild vegetation and companion plants to optimize the conservation of natural enemies and their effectiveness at the crop level, the management of insecticide resistance, and the improvement of sex pheromone-based tactics.

Semiochemicals

Organisms coordinate their interactions using indirect communication based on chemical substances known as semiochemicals. Semiochemicals include pheromones, which handle coordination between organisms of the same species, and allelochemics (e.g., allomones, kairomones, synomones, and apneumones), which handle coordination between organisms of different species (Kasinger et al. 2008). Because semiochemicals elicit behavioral responses in recipient organisms, they have been widely used in pest management (Tarusikirwa et al. 2020a).

Synthetic pheromone lures, provided by Delta traps or pan traps, are used to capture male insects, to detect the occurrence of insects, and to monitor population fluctuations, all of which inform decision-making during the bio-pesticide application period (Fig. 6) (Shahini et al. 2021).

Studies on the efficacy of pheromones in controlling *T. absoluta* have produced varying results. In Brazil, Michereff Filho et al. (2000) observed the highest levels of interruption in male orientation (60–90%) in tomato plots where round traps containing 35–50 g/ha of sex pheromones were placed; however, the percentage of mined leaflets, bored fruits, and frequency of mating in cages were not noticeably reduced. This was probably due to the composition of the synthetic pheromone, the dosage used, the high

Fig. 6. Implementing the use of pheromone traps as ethological control recommendations of Plant doctors in Bolivia.

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pest population density, and the migration of mating females to the area treated.

Combining biological controls with other ecosystem-friendly tactics has shown promising results. In Colombia, Morales et al. (2014) evaluated the efficacy of combining *A. gelechiivoris* (a biological control) with sex pheromone traps (an ethological control). Compared to the results produced by chemical control, they observed that this combination was more efficient in controlling *T. absoluta*, with a maximum larvae parasitism rate of 68.75%. Similarly, Nazarpour et al. (2016) conducted field studies to determine the short- and long-term effects of *B. thuringiensis* var *kurstaki* (Bt), azadirachtin (AZ), and indoxacarb on *T. absoluta* larvae, including the side effects of indoxacarb on natural predators (*Coccinella septempunctata* L. (Coleoptera: Coccinellidae), *Chrysoperla carnea* (Stephens) (Neuroptera: Chrysopidae) and *Syritta* sp. (Diptera: Syrphidae)). The results indicated that indoxacarb reduced *T. absoluta* density and damages in the short term, while Bt and AZ not only significantly suppressed larval density and led to a 100% reduction in fruit and foliage damage, but also had the fewest adverse effects on predators since with indoxacarb the number of predators diminished from 0.37, 0.21, and 0.08 individuals of *C. septempunctata*, *C. carnea* and *Syritta* sp. to no individuals during the first days after application, while with Bt and AZ mean number of *Chrysoperla* and *Syritta* these predators ranged from 0.29 to 0.66 and 0.04 to 0.08 individuals, respectively after 10 d of application. *Coccinella* did show greater susceptibility to azadirachtin applications.

Goda et al. (2015) tested the efficacy and cost-benefit rate of an IPM package based on the use of sex pheromone aggregation traps, combined with biorational solutions and a biocontrol agent (*T. bactrae*), as compared to conventional management strategies. They concluded that mass trapping, combined with either the release of the parasitoid *T. bactrae* or the application of biorational solutions based on neem or *Streptomyces avermitilis* (ex Burg et al.) Kim and Goodfellow (Actinomycetales: Streptomycetaceae), achieved the highest reductions in *T. absoluta* tomato infestations, resulting in higher yield production and cost reductions of up to 57.19%.

In Argentina, light traps supplemented with LED (Light Emitting Diode) 470 nm used in combination with sex pheromones were able to catch a higher number of tomato leaf miner adults. Lepidoptera species are equipped with light receptors that make them sensitive to blue light. When the light reaches a peak close to 460 nm, it coordinates with pheromones in signaling adult insects, making them easier to catch (Castresana and Puhl 2016).

Given the beneficial effects of pheromones, future research on their use in pest control should focus on formulations that facilitate field dispersion, as well as on the optimization of controlled-release technologies and trapping efficiency. Further research on the chemical ecology of insect pests and compatibility with other pest management tactics is crucial for the development of semiochemical-based insect management programs (El-Shafie and Romeno Faleiro 2017).

Regardless of the method used, it is essential to consider a periodic monitoring program for *T. absoluta* that allows the farmer to detect the presence or arrival of the pest on tomatoes or other host plants, estimate population levels over time, obtain information on pest distribution, and assess the effectiveness of management practices (OIRSA 2015). According to OIRSA, monitoring should be utilized in high-risk areas upon entry, considering the presence and distribution of alternative host plants and ensuring homogeneous coverage of the entire cultivation area. Emphasis should be placed on the edges and center of the area to detect damage, focusing on young leaves and the peduncles of the fruits.

Monitoring techniques should be customized to the development stage of the insects. Allache and Demnati (2020) recommended using pheromone-baited Delta-type traps set 1.20 m from the ground surface to capture adults at weekly intervals to detect the beginning of adult flight, as well as to study population changes. For the immature stages (eggs, larvae, and pupae), they recommended that all plant parts should be sampled, with a focus on leaves and fruits.

In conclusion, the effective and sustainable management of *T. absoluta* requires the integration of cultural, behavioral, biological, and chemical controls with IPM principles. A number of strategies have been proposed to manage *T. absoluta* populations, including cultural and biological tactics, such as allowing the soil a six-week cultivation-free period, covering it with plastic mulch or solarizing it to prevent pest carry-over from the previous crop, as well as to prevent pest multiplication in alternative plant hosts (especially solanaceous species); installing sticky traps before transplanting; inspecting crops to detect early signs of damage; and placing pheromone-baited traps for monitoring purposes during all stages of tomato production. Other strategies include the establishment of populations of effective biological control agents (predators, parasitoids, and biopesticides) in combination with a set of officially registered low-toxicity, selective pesticides, to be used in rotation (IRAC 2011, Illakwahhi and Srivastava 2017).

T. absoluta Management From a Plantwise Perspective

Plantwise is a global program led by the Centre for Agriculture and Bioscience International (CABI), which helps farmers handle plant health problems through a national network of plant clinics, which are established in each country where the program is being implemented. It is run by trained plant doctors, from whom farmers can obtain practical advice. There are currently more than 3,700 plant clinics in 34 countries around the world, where plant doctors provide diagnoses and management advice for any problem and any crop, benefitting farmers who need help with the plant pests and diseases affecting their crops (CABI 2019).

In Latin America and the Caribbean, Plantwise operates in Barbados, Bolivia, Brazil, Costa Rica, Grenada, Honduras, Jamaica, Nicaragua, Peru, and Trinidad and Tobago. Despite its efforts, however, smallholders and subsistence farmers do not always have access to Plantwise's services. Owing to a lack of technical support against pests and diseases, they frequently suffer substantial crop losses. In addition to this lack of access, public institutions have dedicated few human resources to extension and technology transfer, and extension budgets generally are small. In the absence of viable alternatives, smallholder often relies on pesticides and the potentially biased advice of agro-input dealers when dealing with crop pests. Besides the potential overuse of chemicals and consequently reduced yields, this might have a serious impact on health, the environment, and production economics (Klerkx et al. 2016). Additionally, Latin American and Caribbean countries that use extension methods tend to focus on one-on-one on-site advice sessions, which are expensive for their respective governments. The Plantwise clinic system has been shown to reach more people at a lower cost, and provides farmers with alternative, neutral advice. It has also promoted the reduced use of chemicals, with the result that a number of smallholder farmers have stated that, with the advice they received from plant doctors, they were able to reduce crop losses (CABI 2016, Barrantes-Bravo et al. 2017).

In Bolivia, plant clinics were established in the departments of Santa Cruz and Cochabamba (Fig. 7). These are considered a

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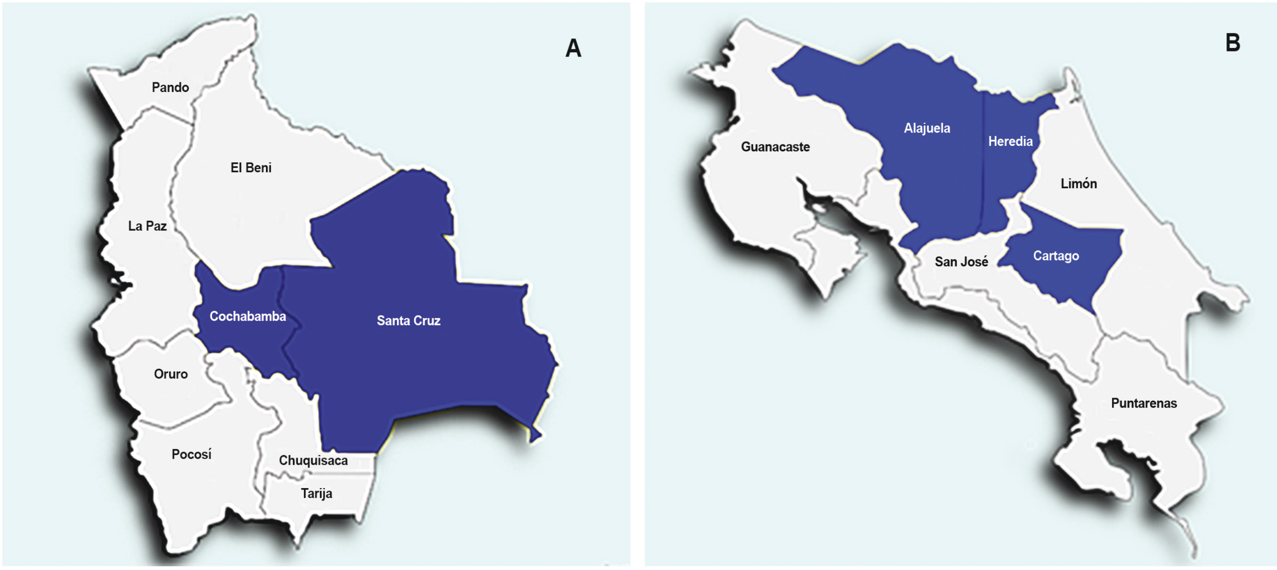

Fig. 7. Geographical influence of plantwise clinics in Bolivia (A) and Costa Rica (B) supporting management of *T. absoluta*.

standard procedure to enhance the technical abilities of extension officers and farmers, and there is evidence that they have led to increased crop yields and quality (CABI 2016). Although Costa Rica is one of the last countries to partner with Plantwise, efforts have been made to implement plant clinics in collaboration with key institutions in the country. All Plantwise countries have developed pest management guides called 'Green and Yellow Lists' with the help of experts in entomology, phytopathology, nematology, and acarology, as well as agricultural extension agents from different institutions (e.g., public universities, the Ministry of Agriculture and Livestock, and research institutes) to develop precise advice on dealing with some of the most important pests, including *T. absoluta* in tomato (CABI 2014).

In a recent study exploring how communication and its technical content shape farmers' responses to advice delivered at plant clinics in Malawi, Nepal, and Costa Rica, it was shown that the main beneficiaries of the plant clinic system are smallholder farmers who receive at least one diagnosis for a plant health problem and up to six options for managing the problem. These recommendations are given verbally and then reinforced with a written prescription form that summarizes the recommendation (Bentley et al. 2018). The authors found that 74% of plant clinic farmers (including tomato growers) accepted advice to apply pesticides, including on organic farms, but only 54% decided to use cultural or biological controls.

Based on the positive effects of the plant clinics on smallholder farmers, we analyzed their impact in relation to *T. absoluta* in Latin America. Bolivia and Costa Rica were selected for this study based on the amount of data available on *T. absoluta* diagnosis and management. Bolivian Plantwise clinics have yielded valuable information on the incidence and control of *T. absoluta* from 2012 up to the present, while Costa Rican clinics have provided information dating back to 2018.

The plant clinics have allowed us to determine the distribution of *T. absoluta* and identify the tomato cultivars most frequently associated with this pest in Bolivia and Costa Rica (Table 2). In Costa Rica, a higher number of reports have been received from nine localities in Alajuela Province, where *T. absoluta* feeds on eight cultivars (Rambo, Cinco, Cinco 7810, Cinco 8565, Vulcano, Milano, Millán, and 7834). In Bolivia, it is distributed across five departments. It is most widespread in the department of Santa Cruz, where it has been reported in 49 different localities, followed by Cochabamba (five localities), Chuquisaca, Tarija, and Tiraque (one locality each).

In Bolivia, *T. absoluta* management recommendations have evolved from 2012 to 2018. When the plant clinics were first established, farmers were predominantly advised to use chemical control; from 2012 onwards, however, chemical use diminished and got steady, reaching levels between 35 and 49% (Fig. 8). Meanwhile, alternative management strategies (e.g., biological, ethological, and cultural controls) began to increase in Bolivia, as a consequence of the influence and recommendations of the plant clinics, following the uptake of the recommended practices at field level. During Plantwise implementation, the technicians who delivered the technical advice to the farmers when visiting the plant clinics, were also trained in IPM and were thus familiarized with more sustainable methods of managing the key pest population (Fig. 9A–D). Cultural control-based recommendations, including lower-leaf pruning and elimination of crop residues and infested fruits, among others, have shown a steady increase in those good agricultural practices since 2014. As shown in Fig. 8, those cultural control-based recommendations reached levels between 35 and 31.8% in 2016 and 2017, respectively, similar to the 2016 chemical control levels. Ethological control recommendations, such as the use of pheromone traps, increased from 2014 to 2016 (12–15%), and it was more significant in 2017 and 2018 reaching a range of 25–27.1%. Biological control recommendations increased from 2013 to 2014, but generally decreased from 2014 onwards. Concomitantly, during the field visits implemented every week by the technicians, it was observed a similar level of adoption of those recommendations at the field level. Based on data gathered from fieldwork and observations, this fluctuation seems to have been caused by the availability and commercialization of biological control products in each area of the country where the pest was reported, as well as the experience of the technicians delivering the recommendations. Unfortunately, the technicians can have a high turnover rate, and their contracts can be interrupted based on the available budget of their respective institutions or municipality. Turnover can also be affected for political reasons.

Fortunately, the plant clinics in Costa Rica have benefitted from the experience gained in Bolivia as much as from the priority given

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Table 2. Locations and cultivars of tomatoes associated with *T. absoluta* in Bolivia and Costa Rica

Province	Locality	Cultivar
Bolivia		
Chuquisaca	Tapial	Hybrid Orna
Cochabamba	Chanka	Orna
	Esmeralda	Lia
	Mendes Mamata	Rio Fuego
	Omereque	Rumi
	Pacay	Lia
	Omereque	Pera
Santa Cruz	Agua Clara	Icaro; Lia; Orna; Supremo; Superman
	Agua Clarita	Bonanza; Lia; Omereque
	Algodonal	Lia; Wichol
	Bella Victoria	Bonanza
	Bella Vista	Bonanza; Lia; Orna
	Cañon de Segura	Rio Fuego
	Chirimoyaicito	Lia; Wichol
	Chirimoyita	Lia
	Comarapa	Lia; Nativo; Wichol
	El Bado	Lia
	El Castillo	Lia
	El Cementerio	Bonanza; Hibrido
	El Pacay	Lia; Omereque
	El Sindicato	Icaro; Santa Clara
	Filadelfia	Lia; Santa Clara
	Fondo Tierras	Lia
	Hierba Buena	Milagro
	Infiernillo	Bingo; Hibrido Bonanza
	La Barranca	Bonanza; Huichol; Icaro; Lia
	La Colpa	Lia
	La Colonia	Lia; Omereque; Superman
	La Junta	Lia
	La Piedra	Lia
	Las Barreras	Bonanza
	Las Cruces	Lia
	Los Gallos	Bonanza
	Los Negros	Bonanza
	Mairana	Hybrid Lia; Nativo; Perseo; Superman
	Mendiola	Bonanza; Lia
	Monteagudo	Lia
	Nueva Esperanza	Santa Clara
	Pampagrande	Hybrid Bonanza; Nativo; Hibrido Lia; Hibrido Rumy; Lia; Perceo
	Pie de la Cuesta	Lia
	Pozuelo	Lia; Rio Grande; Orna
	Puerto Limón	Lia
	Pulquina	Lia
	Quirusillas	Lia; Pera; Santa Clara; Hibrido Taison
	Rio Abajo	Lia (Hibrido)
	Saipina	Eureka; Lia; Regina Semilla Sacada
	San Isidro	Hybrid Lia; Lia
	Sindicato	Lia
	Venadillo	Lia; Rio Grande
	Viana	Rio Grande
	Villa Eccehomo	Hibrido; Lia Icaro; Lia
	Witron	Lia
Tarija	Cercado	Pamela
Tiraque	Pueblo	
Costa Rica		
Alajuela	Calle Sainal	Rambo
	La Luisa	DRW 7810; Rambo
	Rosales	El Cinco;
	Sabanilla	El Cinco; DRW 7810; Vulcano
	San Luis	Milan
	San Pedro	7834; El Cinco, FDR 8565
	San Rafael	El Cinco, RDW 7810; Rambo; Rambo 8565; FDR 8565; Vulcano
	Trojas	El Cinco
Cartago	Tucurrique	JR Special

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by the Costa Rican government to more sustainable methods of control. As a result, plant doctors are able to make recommendations based on alternative methods of managing *T. absoluta* populations, and tend to recommend biological control tools, such as *Bacillus thuringiensis*, in combination with ethological methods, such as pheromone traps (Fig. 10).

Though chemical control is still recommended to farmers in both countries, these recommendations have been made following Plantwise guidelines and incentives for the use of pesticides less toxic to human. Most products belong to a moderately hazardous group (class II) or have a lower level of toxicity, such as flubendiamide, clorfenapyr, lufenuron (Table 3). Following Plantwise implementation in Bolivia and Costa Rica, both countries have seen a rise in their number of sustainable recommendations, having the use of pheromones as one of the most frequent recommendations given to farmers (Fig. 11). The level of adoption of the given recommendations was monitored and evidenced through the field visits carried out by the technicians assigned to

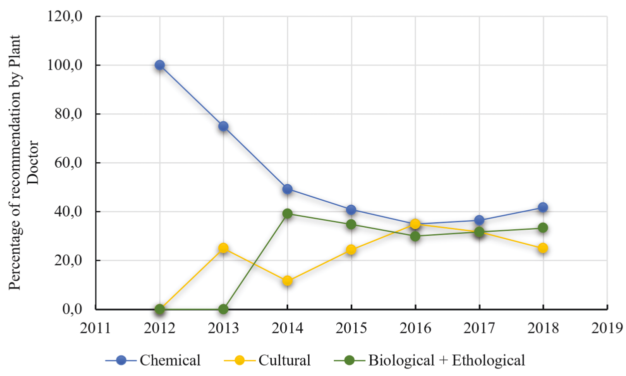

Fig. 8. Variations in *T. absoluta*'s management recommendations in Bolivia (2012–2018).

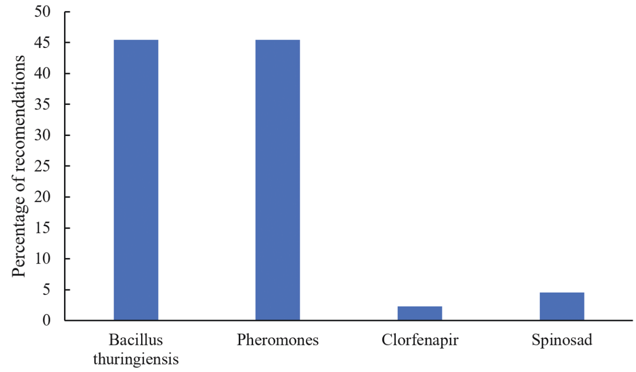

Fig. 10. Strategies for managing *T. absoluta* populations in Costa Rican tomato crops in 2018.

Fig. 9. Plant clinics in Bolivia: Field visits and monitoring of field conditions by plant doctors in Bolivia (A, B); diagnosis in a plant clinic (C, D).

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Table 3. List of insecticides commonly recommended by plant doctors to manage *T. absoluta* in Bolivia and Costa Rica

Insecticide (active ingredient)	Human toxicity[a]	Classification	Frequency of prescriptions
Bolivia			
Terbufos	Extremely hazardous	Class Ia	0.8
Methomyl	Highly hazardous	Class Ib	0.4
Cartap	Moderately hazardous	Class II	0.8
Chlorfenapyr	Slightly hazardous	Class III	4.0
Chlorpyrifos	Moderately hazardous	Class II	4.0
Chlorpyrifos + cypermethrin	Moderately hazardous	Class II	0.4
Flubendiamide	Slightly hazardous	Class III	1.2
Lambda-cyhalothrin + thiamethoxam	Moderately hazardous	Class II	6.5
Lufenuron	Slightly hazardous	Class III	22.9
Flufenoxuron	Unlikely to present acute hazard with normal use	Class IV	1.6
Metaflumizone	Unlikely to present acute hazard with normal use	U	22.9
Methoxyfenozide	Moderately hazardous	Class II	0.4
Teflubenzuron	Moderately hazardous	Class II	16.1
Triflumuron	Unlikely to present acute hazard with normal use	U	0.8
Chlorantraniliprole	Nontoxic	No classification	13.7
Mineral oil			1.2
Alpha cypermethrin + teflubenzuron	Moderately hazardous	Class II	0.8
Costa Rica			
Indoxacarb	Moderately hazardous	Class II	60.0

[a]Toxicity based on WHO classification (WHO 2020).

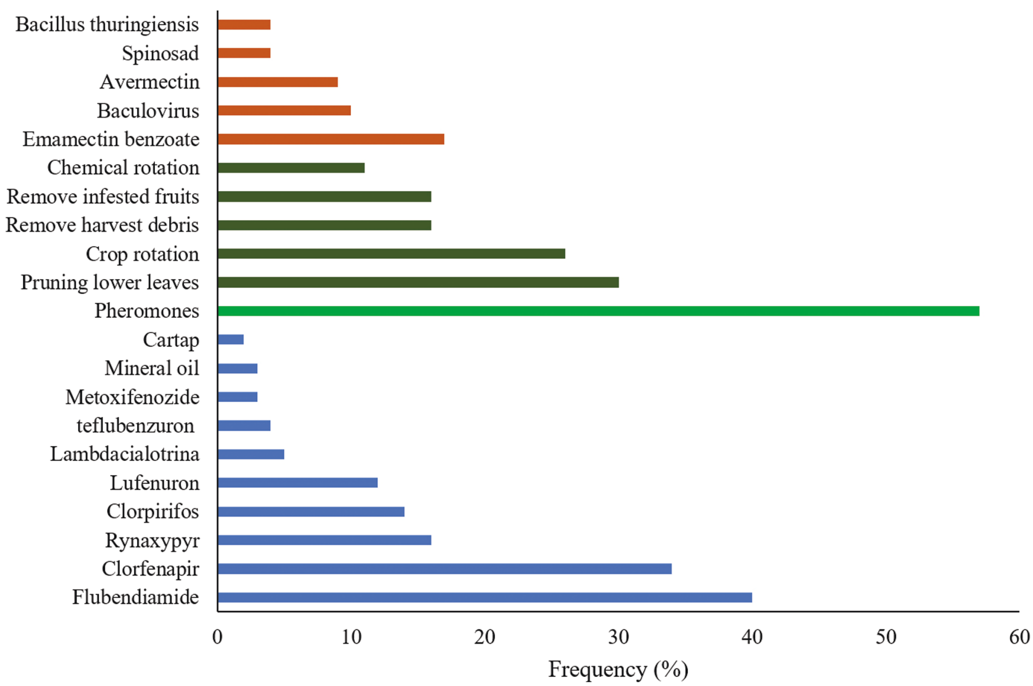

Fig. 11. Frequency of sustainable recommendations given by plant doctors in 2018.

each region, who work with groups of producers in each municipality. In this way we can highlight that the level of adoption always exceeded the level of the recommendations given, because it was transferred from one producer to another, spreading the practice among the community of farmers. According to Desneux et al. (2021) management options such as trapping and use of pheromones, cultural tactics and warning and early diagnosis (pheromone-based monitoring) are equally applied as important components within IPM packages in native and invaded areas, indicating that although these options can be less effective if applied alone, they could be considered as permanent, complementary tools to other more effective options such as chemical control and/or biological control.

Conclusions

Tuta absoluta is a key pest of tomato crop since severe yield losses caused worldwide as it is widely distributed. Efforts are being made to manage this pest by using eco-friendly and safe management tools, other than the use of more selective pesticide chemical molecules, including biological control, use of pheromones, development of resistant tomato cultivars which could be applied in *T. absoluta* management programs. More programs focused on grower's capacity

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building should be implemented to increase the uptake of these sustainable strategies at the field level. It is important to highlight the need to work with the technicians and growers in the identification of the most susceptible development stages of *T. absoluta* to apply proper and effective management.

Farmer responses to innovation are very complex. Their acceptance or rejection could depend on several factors, but the predominant influence is how a given innovation is communicated to them. Thus, it is important to consider the logistics of the transfer of knowledge, such as the use of common words, adjusted to the education of each farmer, and the use of proper didactic resources. As demonstrated in Bolivia and Costa Rica, the Plantwise program has brought substantial changes to the ways in which farmers deal with pests, including *T. absoluta*. In this context, the trend of substituting or complementing chemical control with more sustainable strategies could be partially attributed to the plant doctors, who are continually trained to explain and demonstrate the benefits of pest management strategies other than chemical control.

Plant doctors frequently participate in customized training courses designed by CABI, which are built on their existing knowledge and show them how to maximize their skills when diagnosing problems and giving recommendations. The CABI-designed training program has helped increase the performance of extension personnel; the motivation of the extension advisors can be achieved using several techniques, including experiential training, one of the pillars on which CABI training is based. Positive performance outcomes can impact the extension advisor's ability to efficiently carry out a given task, giving them the confidence to perform similar tasks in the future. Reducing the overuse of insecticides in tomatoes alongside a higher IPM adoption rate provided a great case study illustrating the importance of field extensionists in advising growers. It proved the importance of investing in technology transfer to improve food quality and, from a broader perspective, overall quality of life. The positive results presented here should encourage governments to invest more money in these basic principles. It is certainly much more efficient than attempting to mitigate the consequences associated with the misuse of pesticides, such as pollution, public health issues, and pest resurgence, among other problems.

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