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REVIEW

Biology and Global Impact of the Tomato Leaf Miner *Tuta absoluta* (Lepidoptera: Gelechiidae) with Sustainable Management Approaches

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Abstract

Tomatoes are among the most economically and nutritionally important crops worldwide, yet their cultivation is increasingly threatened by invasive pests and diseases. Among these, the tomato leaf miner (*Tuta absoluta*) is one of the most destructive, causing yield losses from about 11% to 100% under severe infestation. Native to South America, this pest has rapidly spread across Asia, Africa, and Europe due to its high reproductive capacity, ecological adaptability, and rising resistance to conventional insecticides. In addition to tomatoes, it also infests other Solanaceous crops and wild hosts, compounding its spread and impact. Infestations result in extensive foliar, stem, and fruit damage, reducing photosynthetic efficiency, lowering market value, and predisposing crops to secondary infections. These effects pose significant economic challenges and threaten global food security. Integrated Pest Management (IPM) currently represents the most viable control strategy, combining cultural practices, mechanical interventions, biological control agents, and judicious pesticide use. Advances in host plant resistance, pheromone-based monitoring, and eco-friendly biopesticides provide promising tools, yet their effectiveness is constrained by the pest's adaptability and resistance development. Future management requires region-specific, multidisciplinary solutions. Innovative technologies such as RNA interference (RNAi) have shown potential as a targeted, sustainable control method, demonstrating increased larval mortality and population suppression in preliminary studies. This review synthesizes current knowledge on the biology, ecology, and management of *T. absoluta*, while highlighting key research gaps and future directions to strengthen sustainable tomato production globally.

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Statement of Sustainability: Sustainable management of the tomato leaf miner (*Tuta absoluta*) is essential to achieving SDG 2: Zero Hunger by protecting tomato yields, farmer livelihoods, and global food security. Heavy reliance on chemical pesticides has led to resistance and environmental risks, making Integrated Pest Management (IPM) the most viable solution. Approaches such as biological control, pheromone traps, host resistance, and eco-friendly biopesticides reduce crop losses while safeguarding ecosystems. Emerging tools like RNA interference (RNAi) further strengthen control options. Adopting these sustainable strategies ensures resilient tomato production, improved farmer income, and stable food availability, directly contributing to hunger reduction.

1. Introduction

Globally significant crop tomato (*Solanum lycopersicum* L.) is classified within the Solanaceae family, valued for its high nutritional content and economic importance. Rich in vitamins A, B, and C, tomatoes contribute significantly to global diets and agricultural economies (Pandey et al., 2023). This herbaceous plant, evolved from the wild progenitor of cherry tomato (*S. lycopersicum* var. *cerasiforme*) of western Latin America, has exhibited adaptability to varied agro-climatic settings and is now cultivated worldwide (Mattoo, 2014). In 2019, global tomato production spanned approximately 5.03 million hectares, yielding 1.8 billion metric tons annually, with the USA, Turkey, India, and China as the foremost producers (FAO, 2023). Asia alone contributes 54.1% of global tomato production, underscoring its pivotal role in agriculture (Guimapi et al., 2020). Despite this remarkable production, tomato farming faces numerous constraints, both biotic and abiotic, as *Tuta absoluta* emerges as the most severe biotic threat (Desneux et al., 2022).

An invasive pest native to South America, *T. absoluta* was first discovered in 2006 in Spain and quickly expanded throughout Africa, Asia, and Europe because of global commerce and agricultural activities (Desneux et al., 2022). Known for its exceptional adaptability, rapid reproduction, and resistance to chemical pesticides, this pest poses a significant challenge to tomato production worldwide (Wakil et al., 2018). *T. absoluta*, which causes catastrophic production losses escalating up to 100% in tomato crops, was initially discovered in Nepal in 2016 in Kavresthali, Kathmandu (Bajracharya and Bhat, 2018). Since then, the insect has spread to other areas, endangering both the viability of agriculture and the means of subsistence for smallholder farmers who mostly grow tomatoes. The biology of *T. absoluta* is marked by its ability to reproduce prolifically, completing 10–12 life cycles annually, with a developmental period of 26–75 days depending on environmental variables (Wakil et al., 2018). This holometabolous insect undergoes complete metamorphosis and thrives in a variety of agro-ecological zones, further amplifying its threat to tomato production. Larvae of *T. absoluta* are voracious feeders, creating inter-laminar mines in leaves, stems, and fruits. This feeding behavior results in irregular galleries filled with frass, causing defoliation, reduced photosynthetic activity, and premature fruit drop (Mikhail et al., 2016; Moussa et al., 2013). The direct damage inflicted by larvae is compounded by secondary infections from fungi and bacteria, rendering tomatoes unmarketable and significantly reducing yields (Meshram, 2015; Pandey et al., 2023).

Globally, the economic impact of *T. absoluta* is staggering. Sub-Saharan Africa alone reports an annual loss of 1.05 million metric tons of tomatoes, equivalent to USD 791.5 million (Chidege et al., 2017). In Kenya, *T. absoluta* has caused annual losses of 114,000 metric tons of tomatoes, valued at USD 59.3 million. Similarly, in Nepal, where tomato cultivation forms a cornerstone of agricultural livelihoods, the pest has inflicted severe economic and social consequences, leaving farmers struggling to recover from the damage (Yadav et al., 2022). The swift invasion of *T. absoluta* in countries such as Ethiopia, India, and Turkey underlines its strong invasive nature and capacity to acclimate to diverse environmental conditions, further exacerbating its worldwide menace (Aynalem et al., 2021). The global spread of *T. absoluta* is facilitated by its behavioral and physiological characteristics. The pest's nocturnal activity, ability to fly several kilometers, and tendency to hide during the day make its detection and control particularly challenging (Zappalà et al., 2012; Hogea, 2020). Its invasiveness is further supported by a short generation period, wide host range, and high demographic potential, allowing it to establish rapidly in new regions (Desneux et al., 2022). Additionally, the pest's resistance to conventional chemical insecticides poses significant challenges to its management, with overuse of pesticides leading to environmental contamination, human health risks, and reduced biodiversity (Chidege et al., 2017).

In reaction to the growing threat posed by *T. absoluta*, integrated pest management (IPM) strategies have been widely advocated. Preventive measures, such as the use of pest exclusion nets, crop rotation, and strict phytosanitary inspections, are crucial for minimizing infestations (El-Aassar et al., 2015). Monitoring pest populations through pheromone traps and crop surveys provides valuable insights for timely interventions (Pandey et al., 2023). As environmentally friendly substitutes for chemical pesticides, biological control techniques are becoming increasingly popular. These include using entomological as *Bacillus thuringiensis* and fungi, as well as natural enemies like parasitoids (*Trichogramma* spp.) and predators (lady beetles) (Shalaby et al., 2013). Additionally, botanical insecticides derived from plant compounds, including citrus-based biopesticides, have shown promise in managing *T. absoluta* populations while reducing environmental impact (Han et al., 2019; Tarusikirwa et al., 2020). Despite the proven efficacy of these techniques, their widespread adoption in regions like Nepal and India remains limited due to a lack of farmer awareness, inadequate access to sustainable pest control technologies, and insufficient infrastructure for implementing IPM practices (Yadav et al., 2022; Pandey et al., 2023).

This review aims to provide a comprehensive grasp of biology, economic impact, and management alternatives for *T. absoluta*, offering valuable insights for researchers and farmers seeking to mitigate its effects and promote resilient tomato production systems globally.

2. Insect Pests Pressure in Tomato Cultivation

One of the biggest barriers in tomato cultivation worldwide is insect pests, which harm plants directly and serve as carriers of several infectious diseases, such as nematodes, bacteria, fungi, and viruses (Aynalem, 2022). Particularly harmful are lepidopteran insects such as bollworms (*Helicoverpa armigera*), potato tuber moths (*Phthorimaea operculella*), and tomato leaf miners (*T. absoluta*) (Shiberu and Getu, 2018). The larvae rely on their mandibulate mouthparts to feed on tomato plants, which results in poorer yields and worse-quality fruit (Kristensen et al., 2007; Krenn, 2010). These pests not only cause direct feeding damage but also make it easier for dangerous infections to enter, which has an additional negative effect on crop health (Aynalem, 2022).

To create entrance places for secondary infections, *T. absoluta*, for example, burrows into stems, fruits, and leaves (Bajracharya and Bhat, 2018; Desneux et al., 2022). The impact on crop productivity is exacerbated by other pests like whiteflies (*Bemisia tabaci*), which spread viral illnesses like the tomato yellow leaf curl virus (TYLCV) (Picó et al., 1996). Likewise, Tomato Spotted Wilt Virus (TSWV) is spread by thrips (*Frankliniella occidentalis*) (Prasad et al., 2020). Due to their quick spread and threat to vast tomato-growing regions, invasive species such as the tomato leaf miner have become a major issue in many places (Aparna and Kumar, 2020; Urbaneja et al., 2012).

3. Origin and Distribution

T. absoluta, a member of the Gelechiidae family, is native to central Chile and was first recorded in Peru in 1917, where it caused severe tomato crop damage (Aynalem et al., 2022). For decades, it remained a significant pest in South America, primarily infesting Solanaceous plants (Abbes et al., 2016). Its global spread began in the early 2000s due to its high reproductive capacity, international trade, and movement of infested plant materials. In 2006, it was unintentionally introduced to Spain, rapidly spreading across Europe and North Africa (Pandey et al., 2023; Rwomushana et al., 2019). By 2013, it reached South Asia, including India, Pakistan, and Afghanistan (Sanda et al., 2018). In Nepal, it was first confirmed in 2016 by NARC surveys in multiple districts (Kadel et al., 2018). Its success is attributed to its endophytic feeding, resistance to pesticides, and adaptability to diverse climates, making it a severe and fast-spreading threat to global tomato production (Bajracharya et al., 2018; Bastola et al., 2021).

4. Host spectrum of *T. absoluta*

Tomato leaf miner (*T. absoluta*) is a highly polyphagous pest, with tomato being its preferred and most economically significant host (Tarusikirwa et al., 2020). It also infests other solanaceous crops such as sweet pepper, eggplant, tobacco, and potato due to their close genetic relationship, which offers ideal conditions for pest development (Megido et al., 2013). In addition to cultivated crops, *T. absoluta* utilizes various wild solanaceous plants like *Nicotiana glauca, Datura stramonium*, *Solanum nigrum*, and *Physalis peruviana* as alternative hosts, enabling survival even in the absence of tomatoes (Biondi et al., 2018; Aynalem, 2022).

Remarkably, the pest has also been reported on non-solanaceous plants such as alfalfa, cowpea, broad beans, and common beans, though these are less preferred (Pandey et al., 2023). This host's flexibility enhances its adaptability and persistence across environments. *T. absoluta* typically lays eggs on the apical foliage of tomatoes, possibly due to lower calcium levels that favor larval development (Yadav et al., 2022). These host-plant interactions suggest potential for breeding resistant varieties as a control strategy. However, the broad host range complicates management (Desneux et al., 2022). Table 1 lists the cultivated and wild plant hosts susceptible to *T. absoluta* infestation.

5. Routes of Infestation in Host Plants

T. absoluta spreads via wind over short distances and through infested tomato fruits, planting materials, and transport items from affected regions (Pandey et al., 2023). The subsequent section highlights the main pathways through which *T. absoluta* disperses:

- **Importation of Tomato Fruits:** Tomato fruits, as the primary host for *T. absoluta*, can harbor hidden larvae during transportation, even without visible damage. Imports of fresh tomatoes from endemic regions like Spain, Italy, and Turkey risk introducing the pest to new areas.

- **Seedlings and Planting Materials:** The transport of tomato seedlings and other solanaceous plants, like eggplants and peppers, from infested areas is a key pathway for *T. absoluta* spread. Early-stage larvae or eggs on leaves can easily introduce the pest to new regions, particularly through imports from widespread areas like South America.
- **Farm Equipment and Vehicles:** Farm equipment, crates, and vehicles can transport *T. absoluta* larvae, eggs, or pupae if not properly sanitized. For example, a vehicle carrying infested crates from a tomato farm in Spain to Bulgaria can spread the pest through contaminated equipment.
- **Production and Packing Facilities:** *T. absoluta* can complete its lifecycle in production facilities, with larvae or pupae developing into moths. Tomatoes infested in such facilities may spread the pest globally.

Table 1. Plant host susceptible to *T. absoluta* infestation.

Host Category	Host Plant Name	Scientific Name	References
Primary host	Tomato	*Lycopersicon esculentum* L.	Desneux et al. (2022)
	Tobacco	*Nicotiana tabacum* L.	Sanda et al. (2018)
Wild Hosts	Black Nightshade	*Solanum nigrum*	Abbes et al. (2016)
	Alfalfa	*Medicogo sativa* L.	Pandey et al. (2023)
	Jimsonweed (Datura)	*Datura stramonium*	Desneux et al. (2022)
	Tree Tobacco	*Nicotiana glauca*	Abbes et al. (2016)
	Cape Gooseberry	*Physalis peruviana*	Abbes et al. (2016)
	Groundcherry	*Physalis angulata*	Retta and Berhe (2015)
	Deadly Nightshade	*Atropa belladonna*	Pandey et al. (2023)
	spiny amaranth	*Amaranthus spinosus* L.	Huda et al. (2020)
	Good-King-Henry	*Blitum bonus-henricus (L.) Rchb.*	Huda et al. (2020)
	Sodom apple	*Solanum coagulans Forssk.*	Huda et al. (2020)
	Fierce Thorn Apple	*Datura ferox* L.	Pandey et al. (2023)
	Jimsonweed (Datura)	*Datura stramonium* L.	Arnó et al. (2019)
	oak-leaved thornapple	*Datura quercifolia Kunth*	Pandey et al. (2023)
	Chilean boxthorn	*Lycium chilense Bertero*	Retta and Berhe (2015)
	cutleaf groundcherry	*Physalis angulate* L.	Retta and Berhe (2015)
	bitter tomato	*Solanum aethiopicum* L.	Retta and Berhe (2015)
	American black nightshade	*S. americanum Mill.*	Pandey et al. (2023)
	silverleaf nightshade	*S. elaeagnifolium Cav.*	Yadav et al. (2022)
	climbing nightshade	*S. lyratum Thumberg*	Retta and Berhe (2015)
	African eggplant	*S. macrocarpon* L.	Retta and Berhe (2015)
	Hairy Nightshade	*S. puberulum Nuttal ex Seemann*	Pandey et al. (2023)
	Noogoora burr	*Xanthium strumarium* L.	Arnó et al. (2019)
	Buenos Aires nightshade	*S. bonariense* L.	Pandey et al. (2023)
Cultivated hosts	Common Bean	*Phaseolus vulgaris*	Retta and Berhe (2015)
	Alfalfa	*Medicago sativa*	Pandey et al. (2023)
Minor hosts	Potato	*Solanum tuberosum*	Pandey et al. (2023)
	Wild Potato	*Solanum spp.*	Retta and Berhe (2015)
	Sweet Pepper	*Capsicum annuum*	Yadav et al. (2022)
	Chili Pepper	*Capsicum chinense*	Pandey et al. (2023)
	Eggplant	*Solanum melongena*	Yadav et al. (2022)
	Pepinodulce	*S. muricatum Aiton*	Yadav et al. (2022)

6. Seasonal Occurrence

T. absoluta, a multivoltine pest, exhibits seasonal activity strongly influenced by climatic conditions. It thrives in warmer temperatures, with optimal development at 30 °C and a thermal threshold range of 14–34.6 °C (Han et al., 2018). Unlike many pests, it can survive at temperatures below 14 °C without high mortality (Han et al., 2018). Diapause does not occur in favorable climates, allowing year-round generations (Tarusikirwa et al., 2020). Mating and oviposition occur nocturnally, with pupation influenced by environmental conditions (Sanda et al., 2018). The pest produces up to four generations from November to May and becomes most active from March to July, especially under warm, dry conditions (Gebremariam, 2015; Bacci et al., 2021; Yadav et al., 2022). In India, infestation positively correlates with maximum temperature during both winter and monsoon seasons (Nayana et al., 2018; Aparna and Kumar, 2020; Aynalem, 2022). In Mediterranean regions, *T. absoluta* completes up to 10–12 generations annually, with life cycles of 29–38 days depending on climate (Pandey et al., 2023; Chidege et al., 2016). Adult moths are nocturnal, sheltering in foliage during the day. Females lay up to 260 eggs on above-ground plant parts, with larvae undergoing four instars and pupating in various locations such as soil, leaves, or mines (Desneux et al., 2022). The pest can overwinter in any life stage-egg, larva, pupa, or adult (Mansour et al., 2019). In tropical areas, population density often declines during the rainy season due to limited host availability (Bacci et al., 2021; Yadav et al., 2022).

7. Life Cycle of *T. absoluta*

T. absoluta, a destructive pest of tomato, undergoes a complete metamorphic life cycle consisting of egg, larva, pupa, and adult stages (Sanda et al., 2018). Development is optimal between 19°C and 25°C, with the cycle from egg to egg-laying adult completed in about 3–4 weeks (Bastola et al., 2021; Sanda et al., 2018). At 10°C, development halts, while high temperatures, though not usually lethal, can adversely affect growth (Aynalem, 2018). The average duration of each stage under laboratory conditions is summarized in Table 2. In conventional tomato-growing regions, the pest can produce 10–12 generations annually (Chidege et al., 2016). Different stages of the life cycle are discussed in detail below.

Table 2. Mean developmental time of life stages under controlled laboratory settings.

S. No.	Life stages	Mean Span (days)	References
1	Egg	3	Bajracharya and Bhat (2018)
2	Larvae	8.2	Yadav et al. (2022)
3	1st instar larva	2.5	
4	2nd instar larva	1.79	
5	3rd instar larva	1.50	
6	4th instar larva	2.68	
7	Pupae	7.11	
8	Adult	18.37	

7.1. Egg

The egg stage of *T. absoluta* represents the initial and highly vulnerable phase of its life cycle. Female moths generally lay between 250–300 eggs during their lifespan, with oviposition occurring predominantly on the underside of host plant leaves, ensuring better protection from environmental factors and natural enemies. Eggs are deposited singly or in small clusters, and although rare, females may occasionally lay them on fruits (Zekeya et al., 2017). Morphologically, the eggs are elongated and oval, measuring around 0.35 mm in length. Initially, they appear oyster-white, gradually turning yellow as embryonic development progresses (Godfrey et al., 2018). Prior to hatching, the eggs darken and may become nearly black, signaling the imminent emergence of larvae. The duration of this stage is strongly influenced by temperature: under optimal warm conditions, hatching occurs in about 7 days, whereas lower temperatures can prolong incubation, delaying larval emergence (Imenes et al., 1990).

7.2. Larva

The larval stage of *T. absoluta* is considered the most destructive phase of its life cycle, as it directly damages host plants. Newly hatched larvae are initially green in color and begin mining into leaf tissues soon after emergence. As they undergo successive molts, their bodies temporarily turn whitish before regaining pigmentation (Ravuri et al., 2023; Pandey et al., 2023). The larval stage typically lasts around 11 days under favorable environmental conditions, though this period may be prolonged under suboptimal circumstances. Development occurs through four distinct instars, during which larvae increase substantially in size, from approximately 0.9 mm in the first instar to nearly 7.5 mm by the fourth instar (Biondi et al., 2018; Ravuri et al., 2023). Throughout these stages, larvae feed aggressively, creating mines in leaves, tunneling into stems, and burrowing into fruits, thereby compromising both yield and quality. Unlike some lepidopteran pests, *T. absoluta* larvae do not typically undergo diapause, unless forced by food scarcity, which contributes significantly to their persistence and survival (Pandey et al., 2023).

7.3. Pupa

The transition from larva to pupa in *T. absoluta* is characterized by a distinct pre-pupal stage, during which larvae cease feeding and exhibit a lighter dorsal coloration as they prepare for pupation (Imenes et al., 1990). Pupation most commonly occurs in the soil, providing physical protection and stable microclimatic conditions, although pupae may also be found on leaf surfaces or inside the characteristic mining tunnels created by larvae. Newly formed pupae are initially green in appearance, but as development progresses, their coloration gradually shifts to chestnut brown, a clear indicator of maturity (Desneux et al., 2022). Pupae generally attain a length of about 6 mm. This stage represents a critical period of metamorphosis, as the insect undergoes extensive internal reorganization and differentiation to form adult structures. Under optimal conditions, the pupal stage lasts approximately 5 days, though variations in temperature and environmental conditions can influence its duration (Pandey et al., 2023).

7.4. Adult

The adult stage of *T. absoluta* marks the reproductive phase of the pest and plays a central role in its rapid spread and infestation potential. Adult moths are relatively small, measuring 5–7 mm in length, and can be identified by their thin, filiform antennae and wings covered with silvery-grey scales (Desneux et al., 2022). A distinctive morphological feature is the presence of conspicuous black patches on the forewings, which aid in identification. Adults are primarily nocturnal, remaining hidden between plant leaves during the daytime to avoid predation. Females generally live longer than males, with an average lifespan of 10–15 days, during which they can lay up to 260 eggs, thereby ensuring high reproductive potential (Aynalem, 2018). In contrast, males survive for a shorter period of about 6–7 days. Typically, females are larger than males, reflecting their reproductive role. As the reproductive agents, adults significantly influence both population dynamics and the continued spread of infestations across crops (Yadav et al., 2022).

8. Damage Symptoms of *T. absoluta*

Infestation by *T. absoluta* in tomato plants causes significant damage, starting with consuming the leaf's mesophyll and protecting the epidermis. Larvae produce blotch-shaped mines. (Bajracharya et al., 2018). Mines appear whitish with irregular spots often covered with droppings, leading to yellowing, wilting, necrosis, and ultimately leading to leaf death in extreme instances (Kadel et al., 2018; Desneux et al., 2022; Pandey et al., 2023). Fruits are attacked at all stages, with larvae boring into them, typically near the crown, resulting in abnormal shapes, reduced sizes, visible exit holes, and decay from fungal infections due to accumulated waste (Simmons et al., 2017; Shashank et al., 2015). Infested fruits may drop prematurely, while larvae also form galleries in stems and penetrate apical buds and flowers, disrupting plant growth and causing flower shedding (Tadele and Emana, 2017; Kadel et al., 2018). Wounds created by mining serve as entry points for pathogens, leading to secondary infections (Bastola et al., 2021; Pandey et al., 2023). Severe infestations stunt plant growth, reduce fruit set, and ultimately kill the plant, with young plants being particularly vulnerable to complete destruction within days (Retta and Berhe, 2015). Figure 1 illustrates the typical damage symptoms caused by *T. absoluta* larvae.

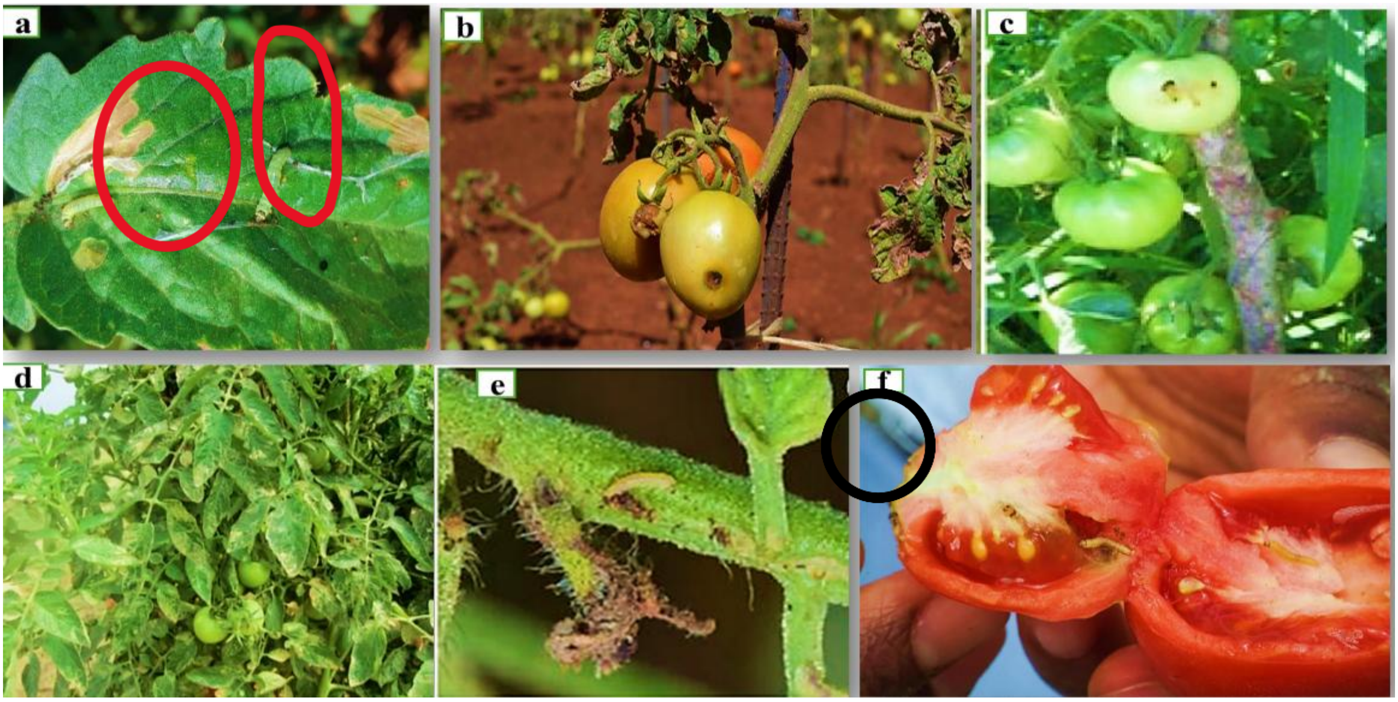

Figure 1. Damage symptoms of larvae (a) Mining Leaf, (b) at severe infestation, (c) boring Fruit, (d) *Liriomyza spp.* infestations, e) feeding on the stem, f) feeding Internal fruit

9. Yield Losses of Tomato Due to *T. absoluta*

T. absoluta poses a major threat to tomato production, with yield losses ranging from 11% to 100% depending on infestation severity and management effectiveness (Mikhail et al., 2016; Tarusikirwa et al., 2020). These yield losses are detailed in Table 3. The larval stage is the most destructive, feeding on leaves, stems, buds, flowers, and fruits, thereby reducing crop quality and marketability (Huda et al., 2020; Hogea, 2020). Larvae bore into immature and ripe fruits—often beneath the calyx—creating initially hidden entry points that later develop into larger exit holes filled with frass (Yadav et al., 2022). This internal feeding causes discoloration, deformation, decay, and premature fruit drop due to secondary infections (Dodfery et al., 2011). Leaf mining destroys mesophyll tissue, turning it necrotic and reducing photosynthesis, ultimately leading to plant dieback (Urbaneja et al., 2012). Globally, *T. absoluta* causes over $50 million in losses annually. In Africa, where tomato production is around 37.8 million tonnes per year, the pest is a significant threat (Rwomushana et al., 2019). In Nepal, yield losses of 30%–80% have been reported, translating to approximately NPR 23 billion (~USD 194 million) in annual financial loss (Bastola et al., 2021). In India, infestation levels have reached up to 95% in greenhouse conditions, leading to severe yield reductions and rising production costs (Nayana et al., 2018).

Table 3. Yield Losses of Tomato Due to *T. absoluta* in Different Parts of the World.

Country	Yield Losses (%)	References
India	Up to 50%	Aparna and Kumar (2020)
Nepal	Up to 100%	Sah et al. (2017)
China	50-100%	Han et al. (2019)
Pakistan	80-100%	Gabol et al. (2023)
Bangladesh	50-100%	Alam et al. (2019)
Ethiopia	60.08%–82.31%	Shiberu and Getu (2018)
Tunisia	11%–43%	Chermiti et al. (2009)
Egypt	Up to 100%	Moussa et al. (2013)
Sudan	80%–100%	Mohamed et al. (2012)
Angola	84%–100%	Chidege et al. (2017)
Zambia	90%	Abass et al. (2019)
Tanzania	90% and 100%	Chidege et al. (2016)
Kenya	50%–100%	Mumo et al. (2024)

10. Management Strategies

The lack of effective management of *T. absoluta* threatens crop yields, food security, and sustainability. Integrated Pest Management (IPM), combining preventive measures, agronomic practices, biological control, and careful pesticide use, offers an eco-friendly and effective approach (Sanda et al., 2018).

10.1. Cultural Practices

Intercropping: Intercropping, the simultaneous cultivation of different crops, serves as an effective and eco-friendly strategy to manage *T. absoluta* by altering its host-finding behavior and lifecycle (Joshi et al., 2018). Aromatic plants like marigold (*Tagetes spp.*) and basil (*Ocimum spp.*) repel the pest, while trap crops such as eggplant and beans divert it from tomatoes. Additionally, flowering species like dill (*Anethum graveolens*) and coriander (*Coriandrum sativum*) attract natural enemies such as Trichogramma spp., boosting biological control in integrated pest management systems (Szczech et al., 2024).

- **Field sanitation:** Field sanitation is vital for managing *T. absoluta* in tomatoes. It includes destroying infested crop residues, fruits, and weeds through burning, burying, or solarization to eliminate breeding sites. Tools from affected fields should be thoroughly cleaned to prevent pest spread (Yadav et al., 2022).
- **Management of plant materials:** Using pest-free transplants is crucial to prevent *T. absoluta* introduction (Retta and Berhe, 2015). Infested plant parts and host weeds like *Lycium chilense*, *Nicotiana glauca*, and *Solanum nigrum* should be promptly removed and properly disposed of to stop the pest's spread (Huda et al., 2020; Yadav et al., 2022).
- **Obliteration of wild and alternate hosts:** Eliminating wild and alternate hosts, such as solanaceous weeds within 50 meters of infested fields, is essential for managing *T. absoluta*, as they act as reservoirs for its development

(Desneux et al., 2010; Yadav et al., 2022). Species like *Nicotiana glauca, Lycium chilense*, and *Solanum nigrum* support egg-laying and infestation, so their removal helps block pest regeneration and spread (Dlamini et al., 2020).

- **Adjusting the planting dates:** Adjusting planting dates is an effective cultural strategy to manage *T. absoluta* infestations in tomato crops. Planting early helps crops escape peak pest periods, while delayed planting may coincide with unfavorable conditions for pest development. In tropical regions, planting during dry seasons has also been shown to reduce infestation levels (Simmons et al., 2017; Giorgini et al., 2019; Yadav et al., 2022).

10.2. Physical Method

Physical control methods play a key role in managing *T. absoluta*, especially in greenhouses, through insect-proof screens, double-entry doors, and outward-facing fans to prevent pest entry (Simmons et al., 2017; Biondi et al., 2018; Pandey et al., 2023). Fine mesh nets (≥9×6 threads/cm^2), pheromone and light-pheromone traps, reflective mulches, and soil solarization are effective non-chemical tools (Megido et al., 2013; Illakwahhi and Srivastava, 2017; Huda and Taj, 2020). Manual removal of infested plant parts and destruction of residues also help reduce pest populations (Retta and Berhe, 2015; Chhetri, 2018). These strategies are most effective when integrated with biological control.

10.3. Mechanical Method

Mechanical methods utilize tools and devices to physically capture or exclude *T. absoluta*, effectively reducing pest populations without chemicals. These techniques alter the reproductive cycles and behavior of pests. While minimizing environmental harm (Desneux et al., 2010; Megido et al., 2013). These are the practices carried out in mechanical methods:

- **Mass trapping:** Mass trapping employs pheromone-baited traps to attract and capture adult male moths, thereby interrupting the mating process and reducing the pest population. Typically, 40–50 traps are placed per hectare in open fields, while greenhouses may require fewer traps due to controlled environments (Gabarra et al., 2015). This technique is cost-effective, environmentally friendly, and works best in combination with other pest control measures (Desneux et al., 2022).
- **Light traps:** Light traps use specific wavelengths to attract nocturnal adult moths, significantly reducing pest populations in areas with low-to-medium infestation levels (Mansour et al., 2019). Solar-powered light traps, which combine light with pheromones, are particularly effective in greenhouses, capturing both males and females (Campolo et al., 2017; Hogea, 2020).
- **Traps baited with sex pheromone lure:** Sex pheromone traps effectively attract male moths, disrupting their reproductive cycle and reducing the population of viable eggs (Gabarra et al., 2015). These traps are widely used for monitoring pest populations and, when implemented in larger numbers, for direct population control (Desneux et al., 2022). Pheromone traps are an essential component of mass trapping systems and are effective in both greenhouse and field conditions (Retta and Berhe, 2015).
- **Insect netting:** Insect-proof netting acts as a barrier, preventing adult moths from accessing tomato plants, and is particularly useful in greenhouse cultivation (Desneux et al., 2013). Nets with a mesh density of at least 9 x 6 threads/cm^2 are recommended to block pests while ensuring proper ventilation and plant health (Megido et al., 2013; Huda et al., 2020). However, netting may reduce colonization by beneficial insects, such as parasitoids, requiring careful integration with other pest control strategies (Desneux et al., 2013).
- ***Covering materials:*** Covering materials, such as plastic sheets and reflective mulches, are used to deter oviposition and create unfavorable conditions for *T. absoluta* (Desneux et al., 2013). Soil solarization, achieved by covering moist soil with transparent plastic during hot weather, kills pupae and larvae, reducing pest carryover between cropping seasons. Reflective mulches also disrupt pest behavior, further minimizing infestation risks (Retta and Berhe, 2015; Campolo et al., 2017; Huda and Taj, 2020).

10.4. Plant-Based Pesticides

Botanical pesticides offer eco-friendly and sustainable alternatives for managing *T. absoluta*, acting through repellence, antifeedant activity, growth inhibition, and direct toxicity while minimizing harm to non-target organisms (Moreno et al., 2012; Tarusikirwa et al., 2020). Neem-based products (*Azadirachta indica*) with azadirachtin disrupt hormonal functions, impairing reproduction and larval development. Melia azedarach extracts alter larval taste perception, reducing feeding, while essential oils from eucalyptus and citronella interfere with molting and metabolism (Sanda et al., 2018). Garlic (*Allium sativum*) acts as a repellent and ovicide, and pepper (*Capsicum annum*) serves as both an antifeedant and contact toxin (Pandey et al., 2023). These plant-based pesticides are most effective when combined with biological control agents like parasitoids and predators, supporting integrated pest management (IPM) strategies (Bastola et al., 2021). Table 4 lists commonly used botanical pesticides, their scientific names, and effectiveness against various life stages of *T. absoluta*.

Table 4. List of plant-based pesticides.

Plants	**Scientific name**	**Stages**	**References**
Toothache Plant	*Acmella oleracea* (L.)	All	Moreno et al. (2012)
Onion	*Allium cepa* L.	Larva 2nd instar	Pandey et al. (2023)
Garlic	*Allium sativum* L.	Larva 2nd instar	Pandey et al. (2023)
Neem	*Azadirachta indica*	Eggs and larvae	Kona et al. (2014)
Bitter Orange	*Citrus aurantium*	Larva	Khaoula et al. (2013)
Coriander	*Coriandrum sativum* L.	All	Moreno et al. (2012)
Lemon grass	*Cymbopogon citratus*	All	Tadele and Emana (2017)
Southern Blue Gum	*Eucalyptus globulus Labill.*	Larvae	Sanda et al. (2018)
Geranium	*Geranium spp.*	Larva	Tarusikirwa et al. (2020)
Jatropa	*Jatropa curcas* L.	Larvae	Moreno et al. (2012)
Chinaberry	*Melia azedarach* L.	Larva 2nd instar	Pandey et al. (2023)
Tobacco	*Nicotiana* species	All	Tadele and Emana (2017)
Basil	*Ocimum basilicum*	Larva	Aynalem (2018)
Pepper	*Piper amalago*	Eggs and larvae	Pandey et al. (2023)
Glabrous Pepper	*Piper glabratum*	Larva	Brito et al. (2015)
Mikanian Pepper	*Piper mikanianum*	Larva	Pandey et al. (2023)
Bitterwood	*Quassia amara*	Larvae	Hogea (2020)
Castor Bean	*Ricinus communis*	Larva	Aynalem (2018)
Jojoba seeds	*Simmondsia chinensis.*	Larva 2nd instar	Pandey et al. (2023)
Thyme	*Thymus vulgaris*	Larva	Aynalem (2018)

10.5. Biocontrol Agents (Natural Enemies)

Natural enemies include beneficial nematodes, parasitoids, predators, and entomopathogenic microorganisms that help to control pest populations by reducing them below economically damaging levels (Desneux et al., 2010; Aynalem, 2018). These organisms are integral to biological control and are recognized for their safety, with no reported adverse effects on non-target wildlife, plants, people, and the environment. Natural enemies can be broadly classified as generalists, which attack a variety of pest species across different genera, or specialists, which specifically target pests from a particular genus or species (Tarusikirwa et al., 2020). Their environmental safety, biodiversity conservation, ecosystem compatibility, and cost-effectiveness make natural enemies a valuable and sustainable option in modern pest management strategies (Aynalem, 2018).

- **Utilization of parasitoids:** Parasitoids are insects that develop parasitically during their immature stages and ultimately kill their hosts before emerging as free-living adults (Strand and Obrycki, 2011). They belong to five major insect orders: Hymenoptera, Diptera, Coleoptera, Lepidoptera, and Neuroptera, with nearly 78% of all known species falling under Hymenoptera (Feener and Brown, 1997; Belshaw et al., 2003). Depending on their biology, parasitoids can be endoparasitoids, developing inside the host, or ectoparasitoids, developing externally. They parasitize eggs, larvae, pupae, or adults, with host location often mediated by olfactory cues from the host or its environment. More than 50 parasitoid species have been reported as effective natural enemies of *T. absoluta*, attacking different developmental stages (Alsaedi et al., 2017). Egg parasitoids, for example, prevent larval emergence and can significantly suppress population build-up in early crop stages, while larval parasitoids are crucial during peak infestation, often achieving reductions of 50–60% in field conditions (Abbes et al., 2016; Aynalem, 2022). Pupae-attacking species, though less studied, contribute to breaking the pest's life cycle in the soil. A comprehensive list of parasitoid species, along with their target life stages, is summarized in Table 5.
- **Application of natural predators:** Predators are vital components of biological control programs because they actively consume multiple prey individuals across their lifetime, making them highly efficient in suppressing pest populations (Strand and Obrycki, 2011). Their effectiveness is enhanced by larger body size, specialized predatory adaptations such as powerful jaws, and advanced sensory abilities for prey detection (Desneux et al., 2010). In agroecosystems, predators play a crucial role in keeping pests below economic thresholds, especially in organic and low-input systems where reliance on synthetic pesticides is limited (Tarusikirwa et al., 2020; Yadav et al., 2022). For

T. absoluta, several generalist predators are highly effective. Predatory bugs such as Macrolophus pygmaeus and Nesidiocoris tenuis are particularly important, as they feed on eggs, larvae, and pupae, thereby exerting pressure across multiple developmental stages. Notably, N. tenuis has been reported to reduce leaflet infestations by 75–97% and fruit damage by nearly 100%, demonstrating its potential as a cornerstone of biological suppression (Urbaneja et al., 2012). Other predators, including lacewings, minute pirate bugs, and predatory beetles, contribute additional layers of regulation, particularly in greenhouse environments. A detailed list of predator species and the pest stages they target is provided in Table 6.

Table 5. List of parasitoids used in controlling *T. absoluta*.

Species	**Types**	**Host stage**	**References**
Agathis fuscipennis	Larval parasitoids	Larvae	Loni et al. (2011)
Apanteles dignus	Larval parasitoids	Larvae and pupae	Desneux et al. (2010)
Bracon nigricans	Larval parasitoids	Early instar larvae	Desneux et al. (2010)
Dineulophus phtorimaeae	Larval parasitoids	Larvae	Biondi et al. (2018)
Encarsia porteri	Larval parasitoids	Egg	Desneux et al. (2010)
Habrobracon didemie	Larval parasitoids	Larvae	Doğanlar and Yiğit (2011)
Habrobracon nigricans	Larval parasitoids	Larvae	Biondi et al. (2018)
Halticoptera aenea	Larval parasitoids	Larvae	Zappalà et al. (2012)
Necremnus artynes	Larval parasitoids	Larvae	Urbaneja et al. (2012)
Necremnus metalarus	Larval parasitoids	Larvae	Urbaneja et al. (2012)
Necremnus tidius	Larval parasitoids	Larvae	Tarusikirwa et al. (2020)
Neochrysocharis formosa	Larval parasitoids	Larvae	Zappalà et al. (2012)
Pnigalio cristatus	Larval parasitoids	Larvae	Doğanlar and Yiğit (2011)
Pseudapanteles dingus	Larval parasitoids	Larvae	Desneux et al. (2010)
Pteromalus intermedius	Larval parasitoids	Larvae	Doğanlar and Yiğit (2011)
Retisympiesis phthorimaea	Larval parasitoids	Larvae	Desneux et al. (2010)
Temelucha anatolica	Larval parasitoids	Larvae	Tarusikirwa et al. (2020)
Trichogramma achaeae	Egg parasitoids	Egg	Tarusikirwa et al. (2020)
Trichogramma bourarachae	Egg parasitoids	Egg	Desneux et al. (2010)
Trichogramma dendrolimi	Egg parasitoids	Egg	Tarusikirwa et al. (2020)
Trichogramma exiguum	Egg parasitoids	Egg	Desneux et al. (2010)
Trichogramma fasciatum	Egg parasitoids	Egg	Tarusikirwa et al. (2020)
Trichogramma lopezandinensis	Egg parasitoids	Egg	Desneux et al. (2010)
Trichogramma nerudai	Egg parasitoids	Egg	Desneux et al. (2010)
Trichogramma pretiosum	Egg parasitoids	Egg	Tarusikirwa et al. (2020)
Trichogramma rojasi	Egg parasitoids	Egg	Tarusikirwa et al. (2020)
Trichogramma telengai	Egg parasitoids	Egg	Desneux et al. (2010)
Trichogrammatoidea bactrae	Egg parasitoids	Egg	Desneux et al. (2010)

Table 6. List of natural predators used in controlling leaf miners.

Common name	**Zoological name**	**Effective stage**	**Refrences**
Cucumeris mite	*Amblyseius cucumeris*	Egg, larva	Tarusikirwa et al. (2020)
Swirski Mite	*Amblyseius swirskii*	Eggs, early larvae	Desneux et al. (2010)
Stingless wasp	*Brachygastra lecheguana*	Larvae	Desneux et al. (2010)
Ground beetle	*Calosoma granulatum*	Larva, pupa	Desneux et al. (2010)
Lacewing	*Chrysoperla carnea*	Eggs, neonate larva	Backer et al. (2014)
Twice-stabbed lady beetle	*Coleomegilla maculata*	Egg, larva	Desneux et al. (2010)
Red-shouldered ladybug	*Cycloneda sanguinea*	Egg	Tarusikirwa et al. (2020)
Wandering Dicyphus Bug	*Dicyphus errans*	Eggs, larvae	Yadav et al. (2022)
Moroccan Dicyphus Bug	*Dicyphus maroccanus*	Eggs, larvae	Tarusikirwa et al. (2020)
Tomato bug	*Dicyphus. tamaninii*	Egg, larva	Tarusikirwa et al. (2020)
Green mirid	*Engytatus varians*	Egg	Rostami et al. (2018)
Predatory shield bug	*Eriopsis conexa*	Egg	Desneux et al. (2010)
Vespiform thrips	*Franklinothrips vespiformis*	Larvae	Wakil et al. (2018)
Striped earwig	*Labidura riparia*	Pupae	Tarusikirwa et al. (2020)
Dwarf Mullein Bug	*Macrolophus caliginosus*	Egg, larva	Desneux et al. (2010)
Macrolophus Bug	*Macrolophus pygmaeus*	Egg, larva	Yadav et al. (2022)
Iberian damsel bug	*Nabis ibericus*	Larvae	Tarusikirwa et al. (2020)
Mirid bug	*Nesidiocoris tenuis*	Egg, larva	Desneux et al. (2010)
Minute pirate bug	*Orius albidipennis*	Larvae	Desneux et al. (2010)
Insidious flower bug	*Orius insidiosus*	Larvae	Desneux et al. (2010)
Striped Lynx Spider	*Oxyopes lineatus*	All stages	Backer et al. (2014)

Table 6. Continued …

Brown stink bug	*Podisus nigrispinus*	Larvae	Desneux et al. (2010)
Sylveira's Paper Wasp	*Protonectarina sylveirae*	Larvae	Wakil et al. (2018)
Tropical fire ant	*Solenopsis geminata*	Larva, pupa	Tarusikirwa et al. (2020)
Raspberry crazy ant	*Solenopsis saevissima*	Larva, pupa	Desneux et al. (2010)
Social Wasps	*Vespidae sps.*	Larvae	Yadav et al. (2022)

- **Application of insect-parasitic nematodes:** Entomopathogenic nematodes (EPNs) are unsegmented, cylindrical organisms extensively utilized as biological control agents that aim to control *T. absoluta*, particularly its soil-dwelling stages (Alikhani et al., 2019). Nematodes from families such as Heterorhabditidae and Steinernematidae, including *Heterorhabditis bacteriophora* and *Steinernema carpocapsae*, are highly effective against pre-pupal and pupal stages of the pest. These nematodes enter the host via natural openings and release symbiotic bacteria, inducing septicemia and leading to death within 48 hours (Aynalem, 2022). EPNs have shown remarkable efficacy, with *S. carpocapsae* and *H. bacteriophora* achieving 89–91% and 92–96% larval mortality in laboratory conditions, respectively, and 48–51% control in greenhouse experiments. In bioassays, *Steinernema feltiae* demonstrated strong infectivity, achieving 77–92% infection in larvae within leaf galleries and reducing tomato infestation by 87–95% in pot trials (Desneux et al., 2007). Additionally, these nematodes are particularly potent against fourth-instar larvae, achieving 77–97.4% mortality, although their effectiveness diminishes for first-instar larvae, with mortality rates of 36.8–60% (Tarusikirwa et al., 2020).
- **Application of insect-pathogenic fungi:** Heterotrophic and filamentous, entomopathogenic fungi (EPF) reproduce through both sexual and asexual spores and belong predominantly to the phylum Ascomycota (Abdel-Baky et al., 2021). Species such as *Metarhizium anisopliae*, *Metarhizium brunneum*, *Beauveria bassiana,* and *Lecanicillium lecanii* demonstrate significant efficacy against a variety of insect pests, including *T. absoluta*, since they have little effect on the environment, pose little threat to human health, and have limited potential for insect resistance (Aynalem et al., 2022). Spores adhere to the insect's cuticle to start the infection, which results in germination and enzymatic degradation that facilitates mycelial penetration. Once inside, fungal hyphae spread through the hemocoel, causing death via toxification and competition for nutrients. *M. anisopliae* and *B. bassiana* are particularly successful due to their production of exoskeleton-degrading enzymes, including chitinases, lipases, and proteases, which sequentially break down the insect's cuticle components, ensuring efficient infection (Mondal et al., 2016; Aynalem et al., 2022). This ability to persist in hyphal form under dry conditions ensures survival, albeit with reduced dissemination potential (Mora et al., 2018). Studies show *B. bassiana* achieves over 95% larval mortality, outperforming chemical insecticides, while *M. anisopliae* significantly lowers infestation levels compared to untreated controls (Yadav et al., 2022). Additionally, locally sourced fungal strains often outperform commercial formulations, achieving up to 95–100% mortality against *T. absoluta* larvae (Tarusikirwa et al., 2020).
- **Application of insect-pathogenic bacteria:** Entomopathogenic bacteria, including spore-forming genera such as Bacillus and non-spore-forming genera like *Pseudomonas* and *Photorhabdus*, are effective biocontrol agents against insect pests (Sabbour and Soliman, 2014). The most common of these is the Gram-positive, spore-forming bacterium *Bacillus thuringiensis* (Bt). (Koziel et al., 1993). Bt produces δ-endotoxins, hemotoxins, and vegetative proteins that specifically target insect pests by binding to their gut receptors, disrupting metabolic processes, and ultimately causing death through starvation (Aynalem, 2022). The host specificity of Bt toxins, determined by the cry and cyt genes, ensures minimal impact on non-target organisms. For *T. absoluta*, cry1, cry2, and cry9 genes have been identified as particularly effective, causing up to 98% larval mortality (Schnepf et al., 1998; Loni et al., 2011). Bt's effectiveness extends across insect orders, with different cry genes targeting lepidopterans, coleopterans, and dipterans (Koziel et al., 1993; Aynalem, 2022). In addition to crystal proteins, Bt strains produce other virulence factors like phospholipases, chitinases, ß-exotoxins, and proteases, further enhancing their insecticidal activity. Some strains also produce vegetative insecticidal proteins (Vip), which increase their efficacy (Tarusikirwa et al., 2020). The ability of Bt to encode multiple crystal proteins, facilitated by horizontal plasmid gene transfer, underscores its versatility and significance as a biopesticide in insect management. Bt remains a cornerstone of biological control-based targeted pest management techniques with minimal ecological impact and no harm to humans or beneficial organisms (Schnepf et al., 1998).

- **Application of insect pathogenic viruses:** Entomopathogenic viruses, particularly granuloviruses such as *Phthorimaea operculella* granulovirus (PhopGV), are highly specific biocontrol agents effective against *T. absoluta* (Sabbour and Soliman, 2014). PhopGV isolates, collected globally, have demonstrated varying insecticidal activity based on their geographical origin (Carpio et al., 2012). Studies show that a Brazilian PhopGV strain effectively infects *T. absoluta*, contributing to reduced pupation and extended larval phases (Mascarin et al., 2010). Similarly, Colombian granuloviruses VG013 and VG003, obtained from *Tecia solanivora*, and *T. absoluta*, respectively, exhibited potent larvicidal effects (Gómez Valderrama et al., 2018). Baculoviruses, including granuloviruses and nucleopolyhedroviruses (NPVs), infect host cells by entering through the midgut, replicating within, and causing systemic infections that lead to pest mortality. These viruses produce two phenotypes during their lifecycle: occlusion bodies, which protect the virus in external environments, and budded viruses that facilitate internal host infection. NPVs target neonate larvae, disrupting midgut cells and ensuring effective pest suppression. In Colombia, where *T. absoluta* poses significant threats to tomato crops, PhopGV-based biopesticides have shown promise as sustainable substitutes to chemical inputs, providing environmentally friendly pest control strategies (Haase et al., 2015). Table 7 provides a list of entomopathogenic organisms used in insect pest management, including their scientific names and the specific host stages they target.

Table 7. List of entomopathogenic organisms.

Insect-pathogenic organisms	Stage of the host	References
Bacillus thuringiensis	Larvae	González-Cabrera et al. (2011)
Bacillus thuringiensis kurstaki	Larvae	Alsaedi et al. (2017)
Beauveria bassiana	Larvae	Aynalem et al. (2022)
Metarhizium Beauveria	Larvae	Tarusikirwa et al. (2020)
Metarhizium anisopliae	Larvae	Aynalem et al. (2022)
Baculoviruses (NPVs)	Larvae	Gómez Valderrama et al. (2018)
Saccharopolyspora spinosa	Larvae	Tarusikirwa et al. (2020)
Steinernema affine	Larvae	Tarusikirwa et al. (2020)
Steinernema carpocapsae	Larvae	Türköz and Kaşkavalci (2016)
Steinernema feltiae	larvae	Türköz and Kaşkavalci (2016)
Heterorhabditis bacteriophora	Larvae	Türköz and Kaşkavalci (2016)
Phthorimaea operculella granulovirus	Larvae	Mansour et al. (2019)
Lecanicillium lecanii	larvae	Aynalem (2022)

10.6. Inherited Sterility Techniques for Controlling *T. absoluta*

An efficient and long-term method of controlling *T. absoluta*, one of the most destructive tomato pests, is Inherited Sterility (IS). This strategy entails releasing males who have been radiation-sterilized into wild populations to reduce reproductive success (Aynalem, 2018). Mating between irradiated males and wild females results in abnormal offspring with significant reductions in egg hatchability, often leading to sterile progeny in subsequent generations. By continuously introducing partially sterile males, the pest population can be progressively suppressed over multiple generations (Han et al., 2019; Aynalem, 2018). Traditionally, male insects were sterilized using γ-radiation, but modern methods now employ X-irradiators, which are safer and more efficient for sterilization (Aynalem, 2018; Huda et al., 2020). The technique does not harm natural pest management systems and is compatible with biological control and other pest management techniques for enhanced efficacy. For example, the predator *Tupiocoris cucurbitaceus* can effectively prey on the eggs of *T. absoluta* produced from mating with irradiated males, further suppressing pest populations (Mansour et al., 2018). One of the strengths of Inherited Sterility is its environmentally friendly nature, as it avoids the use of harmful chemicals. Additionally, increasing radiation doses can lead to malformed offspring, further aiding in pest population control without affecting non-target organisms or disrupting agroecosystems (Aynalem, 2018).

10.7. Development of Host-resistant Tomato Varieties

Developing host-resistant tomato varieties is a key strategy for managing *T. absoluta* infestations. Breeding programs have focused on incorporating resistance traits from wild counterparts of Solanum species, such as *S. chilense*, *S. lycopersicum*, *S. arcanum*, *S. pennellii*, and *S. corneliomulleri*. These wild species possess alleles associated with resistance, which can be integrated into commercial cultivars (Huda et al., 2020). Biochemical compounds like 2-tridecanone (2-TD) and acyl-sugars, zingiberene (ZGB), have been identified as critical in reducing oviposition rates of *T. absoluta*. Resistant cultivars with higher concentrations of these compounds exhibit significantly lower pest infestation compared to non-resistant varieties (Aynalem, 2018; Han et al., 2019). Modern advancements, such as nano genomics, have further enhanced resistance breeding. Incorporating zinc and titanium dioxide nanoparticles into the genome of indigenous varieties can lead to hybrids with improved pest resistance and higher productivity. These nanoparticles also degrade harmful substances like pesticides and organic pollutants, making them an eco-friendly approach for pest control (Katel et al., 2021; Yadav et al., 2022).

10.8. Chemical-based Pest Management

Chemical insecticides remain one of the primary tools for managing *T. absoluta* because of their rapid action against eggs, larvae, and pupae. Modern insecticides such as spinosyns and diamides have demonstrated particularly strong efficacy, with compounds like Spinosad and Chlorantraniliprole consistently achieving high levels of larval and egg mortality in both laboratory and field conditions (Khani et al., 2020; Moeini-Naghade et al., 2020). Combination treatments, for example, Chlorantraniliprole + Abamectin, have further improved control, with reports of over 90% larval mortality (Gozel et al., 2020). Despite these successes, insecticide resistance has become a growing challenge. Resistance has already been documented to Spinosad, Indoxacarb, Abamectin, and Cartap, with varying fold increases depending on location and pest population (Alsaedi et al., 2017). Over-reliance on chemical sprays—up to 30 applications per season in some regions—exacerbates this problem (Simkhada et al., 2018). While products such as Chlorantraniliprole and Spinosad remain effective in Nepal, their long-term viability is uncertain if resistance management strategies are not adopted (Dlamini, 2020). To ensure sustainable use, insecticide programs should emphasize rotation of active ingredients, integration with botanicals, and combination with non-chemical components of Integrated Pest Management (IPM) (Huda et al., 2020). Table 8 provides a detailed overview of the insecticides currently used against T. absoluta, including their chemical classes and recommended doses.

Table 8. List of chemical insecticides used against *T. absoluta*.

Generic name	Chemical group	Rate	References
Abamectin 0.15% EC	Avermectin	0.3 ml L^{-1}	Yadav et al. (2022)
Chlorantraniliprole 18.5% SC	Anthranilic Diamide	1 ml/3 L water	Huda et al. (2020)
Chlorfenapyr 36% SC	Pyrrole	0.4 ml L^{-1}	Sallamn et al. (2015)
Chloropyriphose 48% EC	Organophosphate	5 ml L^{-1}	Sallamn et al. (2015)
Diafenthiuron	Thiourea	125 cc hl^{-1}	Mansour et al. (2019)
Emamectin benzoate 5% SC	Avermectin	5 gm/16 L water	Rwomushana et al. (2019)
Flubendiamide 39.35% SC	Diamide	1 ml/3-5 L water	Rwomushana et al. (2019)
Imidachloprid 17.8 % SL	Neonicotinoid	0.3 ml L^{-1}	Bastola et al. (2020)
Indoxacarb 15 SC	Oxadiazine	10.8 mg ai L^{-1}	Moeini-Naghade et al. (2020)
Lambada Cyhalothrine	Pyrethroid	1ml L^{-1}	Sallamn et al. (2015)
Lufenuron 50 g L^{-1} EC	Benzoylurea	0.5 ml L^{-1}	Oztemiz (2014)
Methomyl 90% SP	Carbamate	1 gm L^{-1}	Sallamn et al. (2015)
Spinosad 45% SC	Spinosyn	1 ml/3 L water	Huda et al. (2020)
Zeta-cypermethrin	Pyrethroid	232 mg ai L^{-1}	Khani et al. (2020)

10.9. Application of Integrated Pest Management (IPM) Strategies

Despite risks to beneficial arthropods and the rise of pest resistance (Desneux et al., 2007; Biondi et al., 2018), chemical control remains a dominant strategy. However, Integrated Pest Management (IPM) offers a more sustainable alternative by combining biological agents, cultural and mechanical methods, and limited pesticide use (Miranda et al., 2005; Chailleux et al., 2013). Techniques like pheromone traps, microbial insecticides (e.g., *Bacillus thuringiensis*), predatory insects, and selective pesticides have been effective in greenhouse and field conditions (Muniappan, 2016; Sah, 2017; Giorgini et al., 2019; Choudhary et al., 2022). For instance, in Egypt, an IPM package reduced fruit damage to just 1–5% through mass trapping, microbial sprays, and rotational use of selective insecticides (Taha et al., 2013). Early interventions, including healthy seedlings, removal of infested parts, and light/pheromone traps, are crucial from the seedling to harvest stages (Sridhar et al., 2019). Pre- and post-harvest measures like residue destruction and structured IPM modules further enhance long-term control (Yadav et al., 2022). Figure 3 presents the key IPM components for managing *T. absoluta* sustainably.

10.10. RNA Interference (RNAi) as a Promising and Novel Technology

An inventive gene-silencing technique called RNA interference (RNAi) has a lot of potential for controlling insect pests, especially the tomato leafminer, *T. absoluta*. This approach reduces insect gene expression at the post-transcriptional stage by inserting double-stranded RNA (dsRNA) molecules that are complementary to the target genes

(Hannon, 2002). Numerous RNAi-based methods have been investigated for pest management, such as ingestion, direct injection of dsRNA, and the creation of transgenic plants that generate dsRNAs specific to insects (Gordon and Waterhouse, 2007; Katoch et al., 2013). The efficient control of the Colorado potato beetle using chloroplast-expressed dsRNAs is an example of an emerging strategy that uses plastid genome engineering to increase the efficacy of RNA interference (Bock, 2015; Zhang et al., 2015). Similar uses of RNA interference have been successful against *Cylas puncticollis* (Prentice et al., 2017) and *Drosophila suzukii* (Taning et al., 2016). For *T. absoluta*, two main RNAi delivery strategies have been investigated: one involves applying dsRNA formulations directly onto plants, while the other uses genetically modified tomato plants capable of producing dsRNAs that silence crucial insect genes (Camargo et al., 2015). The first studies identified important hormonal pathways as targets, and subsequent studies either absorbed dsRNA from a solution by tomato leaves (Luan et al., 2013) or transiently expressed it through Agrobacterium-mediated infiltration, a technique known as "in planta-induced transient gene silencing" (PITGS) (Leckie and Stewart, 2011). Important genes targeted in these studies were arginine kinase, which is important for energy metabolism (Bragg et al., 2012), and Vacuolar ATPase catalytic subunit A (V-ATPase), which is necessary for cellular energy gradients (Nelson et al., 2000). Silencing these genes resulted in a 60% reduction in their expression levels and an increase in larval mortality rates (Camargo et al., 2016). Furthermore, SID-1 proteins, which promote dsRNA transport and absorption and are crucial for systemic RNAi effectiveness, were found in *T. absoluta* by RNA sequencing. For gene silence to occur, enough dsRNA accumulation is essential (Yu et al., 2012). While incorporating lethal genes into the pest genome provides a long-term control solution across generations, studies have shown that RNAi-based approaches effectively mitigate T. absoluta populations and foliar damage (Zhang et al., 2015; Sanda et al., 2018).

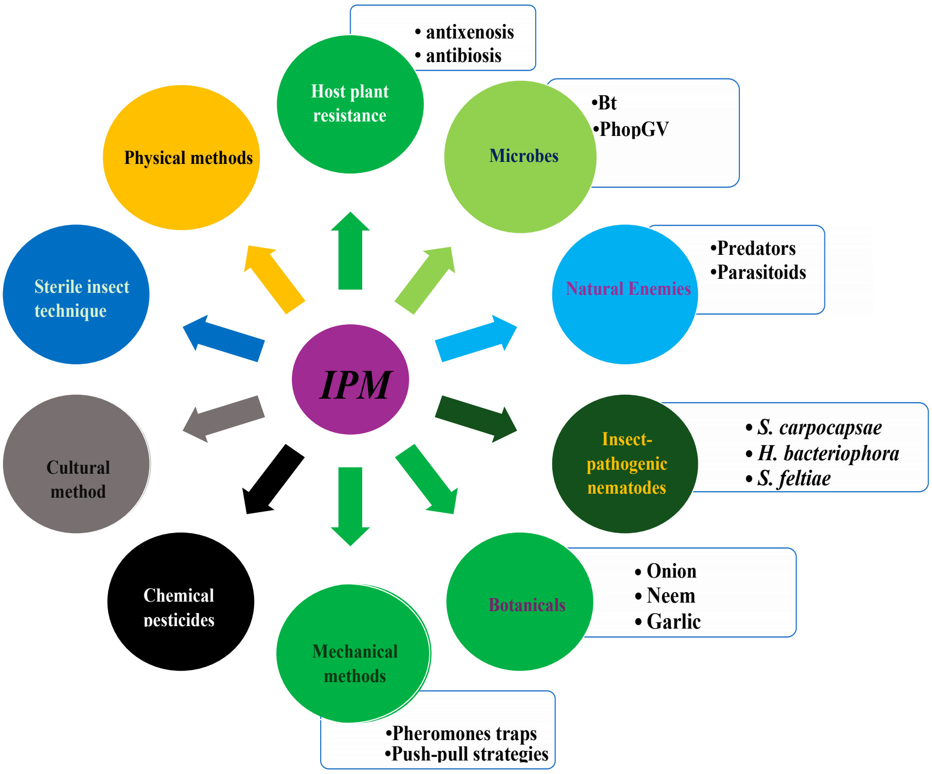

Figure 3. Components of Integrated Pest Management (IPM) (Modified from Tarusikirwa et al., 2020).

11. Future Research Prospective on *T. absoluta*

Future research on *T. absoluta* should emphasize the development of sustainable, region-specific IPM modules that are practical for smallholder farmers and aligned with Sustainable Development Goal 2 (Zero Hunger). While alternative methods such as biopesticides, pheromone traps, entomopathogens, and natural enemies show promise, their large-scale adoption remains constrained by real-world barriers, including high input costs, inconsistent field efficacy, limited extension support, and insufficient farmer training. The lack of reliable market channels for biocontrol agents and the absence of enabling policies further restrict their accessibility. Therefore, future efforts should not only focus on the technical development of management strategies but also address socio-economic and institutional dimensions, such as creating farmer-friendly subsidy schemes, strengthening extension services, and building local capacity through participatory training programs. Moreover, coordinated policy interventions are essential to encourage private-sector involvement in the mass production of biocontrols and resistant varieties. By bridging the gap between technological innovations and field-level adoption, future research can ensure that sustainable management practices are not only effective but also affordable and accessible, ultimately contributing to enhanced food security and the achievement of SDG 2. A comparative synthesis of available management strategies is presented in Table 9 to guide both research priorities and practical implementation.

Table 9. Comparative synthesis of *T. absoluta* management options.

Strategy	**Advantages**	**Limitations**	**Adoption Barriers for farmers**
Chemical pesticides	Rapid suppression; easy availability in agri-shops	Pest resistance; high cost; environmental degradation; health hazards	Dependence on chemicals; lack of safer alternatives
Plant-based pesticides	Biodegradable; eco-friendly; inexpensive; locally available	Short residual activity; variable efficacy depending on preparation and region	Limited awareness; lack of standard formulations and extension
Pheromone traps	Highly effective for monitoring and early detection; reduces pesticide use	Cannot reduce pest populations alone; effectiveness is influenced by density	Cost of traps; technical knowledge gap for farmers
Entomopathogenic fungi and bacteria	Environmentally safe; compatible with IPM; can target multiple life stages	Inconsistent field results; require repeated applications; slow action	Low availability, labor-intensive, and poor market development
Parasitoids and Predators	Long-term suppression; self-sustaining once established	Lack of mass-rearing systems; risk of incompatibility with pesticides	Not commercially available; limited research-extension linkage
Resistant/tolerant varieties	Sustainable and farmer-friendly; reduces pesticide reliance	Still under development; time-consuming breeding programs	Non-availability of resistant seeds in local seed systems
Integrated IPM modules	Combines multiple strategies; reduces resistance risk; cost-effective long-term	Requires coordinated research and farmer training; needs region-specific tailoring	Knowledge gaps, weak extension services, initial higher learning curve

12. Conclusion

T. absoluta continues to threaten global tomato production, but significant knowledge gaps remain that hinder the design of durable and region-specific management strategies. Despite the demonstrated effectiveness of integrated pest management (IPM), limited understanding persists regarding the pest's population dynamics under varying agroecological conditions, its adaptability to diverse climates, and its interactions with indigenous natural enemies. These uncertainties highlight the need for localized research that accounts for regional farming practices, resource availability, and socio-economic constraints. Future research should prioritize the breeding and dissemination of pest-resistant tomato varieties, along with the optimization of biological control agents such as parasitoids, predators, and entomopathogens. Additionally, innovative technologies like RNA interference (RNAi) offer promising avenues for highly targeted suppression of *T. absoluta* populations, but their applicability under field conditions and economic feasibility require further validation. Complementary tools, including pheromone-based monitoring, botanical pesticides, and cultural practices, must also be fine-tuned to specific regional contexts to maximize adoption and sustainability. For successful implementation, farmer awareness and participation are critical. Many growers, particularly in resource-limited regions, face challenges related to financial constraints, lack of training, and restricted access to modern pest management tools. Strengthening extension services, building local capacity for biocontrol production, and ensuring affordable access to eco-friendly technologies are therefore essential. Ultimately, collaborative efforts among researchers, policymakers, industry stakeholders, and farmers will be vital in developing adaptive, region-specific IPM programs. Such coordinated action can reduce reliance on chemical insecticides, safeguard ecosystems, and secure sustainable tomato production in the face of this persistent pest.

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