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Combining alternative pest control methods against *Tuta absoluta*: current evidence and future directions

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With 2 figures and 2 tables

Abstract: *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is an invasive pest causing damage to tomato production worldwide. Synthetic chemical insecticides have proven unsustainable due to resistance development and adverse environmental impacts. Alternative control methods rarely provide sufficient control of *T. absoluta* when used alone. Their effectiveness can be enhanced by integrating them into combined approaches, where strategies reinforce each other to achieve more effective control. Although several combinations of alternative methods have been reported, a synthesis of which combinations have been tested, at what scales, and with what outcomes has been lacking. Here we evaluate the current state of knowledge on binary combinations of alternative control methods against *T. absoluta*. Based on 66 articles comprising 154 experiments identified through a systematic literature search, a Multi-Criteria Decision-Making framework was applied to assess effectiveness of the combinations across small, semi-field, and commercial scale trials. Our synthesis reveals valuable insights into combined control strategies but also shows that most studies remain confined to small-scale experiments. Current evidence supports prioritizing combinations with proven consistency across scales, especially commercial-scales, such as parasitoid-predator, predator-predator or plant extracts with non-arthropod biological control agents. Strategies relying on plant extracts with arthropod natural enemies frequently undermine efficacy and require cautious application. We highlight the urgent need for more commercial-scale trials, inclusion of controls testing agents alone, and economic assessments to evaluate cost-effectiveness and feasibility. This review provides the first evidence-based roadmap directly relevant to researchers, farmers, and policymakers engaged in crop protection and IPM development against *T. absoluta* and beyond.

Keywords: South American pinworm; *Phthorimaea absoluta*; decision-making method; non-insecticidal methods; economic assessment; biological control; Integrated Pest Management (IPM); parasitoids; predators

1 Introduction

The tomato pinworm, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), is the most destructive insect pest of tomato, causing severe damage and substantial yield losses in the absence of effective control strategies (Biondi et al. 2018; El-Shafie 2020). Native to Peru, where it was first reported in 1917, *T. absoluta* spread throughout South America over subsequent decades and was already recognized as a notorious invasive species on the continent in the 1960s, prompting extensive regional research in particular during the 1980s and 1990s (Guedes & Picanco 2012). This provided a critical groundwork for later research conducted following the species' detection in Spain over two decades ago, from where it rapidly expanded to more than 120 countries across Europe, Africa, and Asia (Mansour et al. 2018; Han et al. 2019). This pest poses a significant threat to tomato production primarily and, to a lesser extent, other solanaceous crops, including pepper (*Capsicum* spp.), tobacco (*Nicotiana tabacum*, L.), potato (*S. tuberosum*, L.), and eggplant (*S. melongena*, L.) (Santana Jr et al. 2019).

Chemical insecticides, historically the main method against *T. absoluta*, have proven increasingly ineffective due to endophytic larval feeding, reducing direct exposure and the increasing emergence of resistance (Silva et al. 2016; Guedes et al. 2019; Bavithra et al. 2024). Resistance was first reported in South America to organophosphates and pyrethroids and has since expanded globally to commonly used insecticides (Haddi et al. 2012; Guedes et al. 2019; Ma et al. 2024). Chemical insecticides may further cause negative impacts on human and environmental health. They can also reduce the efficacy of biological control by harming key natural enemies, sometimes triggering secondary pest outbreaks due to the removal of natural enemy populations (Arnó & Gabarra 2011; Rezaei et al. 2019; Papari et al. 2024). These shortcomings have

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led to the search for alternative management strategies of *T. absoluta* (Biondi et al. 2018; Mawcha et al. 2025).

Several alternative strategies have been investigated and implemented to mitigate *T. absoluta* infestations (Table 1). These include the deployment of biological control agents, application of plant extracts, the use of host plant resistance, sterile insect technique and semiochemicals (Desneux et al. 2022; Mawcha et al. 2025). While each method offers distinct advantages, their individual application has also shown inherent limitations in achieving sufficient suppression of *T. absoluta* (Rwomushana et al. 2019; Desneux et al. 2022). Furthermore, alternative approaches are often acting more slowly than chemical insecticides, require extended establishment periods, may be climatically restricted in implementation, and sometimes demand specialized expertise (Rebek et al. 2012; Collatz et al. 2021; Desneux et al. 2022; Kapranas et al. 2022).

The effectiveness of individual alternative methods can be enhanced by integrating them into combined approaches, where strategies reinforce each other to achieve more sustainable and effective control of *T. absoluta* (Tarusikirwa et al. 2020). While the use of several combinations of alternative methods is reported in the literature, a comprehensive synthesis including information on effectiveness against *T. absoluta* is essential to improve integrated pest control strategies, guide implementation and highlight combinations requiring further research (Han et al. 2024). Understanding binary interactions between control methods will ultimately help to develop integrated control strategies for insect pests beyond *T. absoluta*.

We analyze and discuss binary combinations of selected alternative control methods against *T. absoluta* using a Multi-Criteria Decision-Making approach, assigning decision scores to identify combinations that were effective, neutral, or ineffective. We discuss the factors that might have influenced the recorded outcomes, identify knowledge gaps, and suggest ways to develop and implement future integrated strategies against *T. absoluta*.

Table 1. Alternative control methods that can contribute to the control of *Tuta absoluta*.

Parasitic wasps: Both hymenopteran egg and larval parasitoids have been reported to attack *T. absoluta* and investigated as control options (Ferracini et al. 2019). Mass releases of egg parasitoids from the family of Trichogrammatidae achieved effective control in different world regions (Salas & Ferrer-Wurst 2022; Cherif et al. 2023). Key larval parasitoids can be found in the families of Braconidae and Eulophidae (Ferracini et al. 2019).
To date, only one species (*Dolichogenidea gelichiidivoris*, Braconidae) has been introduced for classical biological control in Kenya with some success under laboratory conditions (Aigbedion-Atalor et al. 2022; Mama Sambo et al. 2022b). The species has also established in Spain and Algeria after accidental introduction (Krache et al. 2021; Denis et al. 2022).
Predatory insects: While numerous predators are reported to attack *T. absoluta*, mirid bugs (Hemiptera: Miridae), preying on eggs and young larvae, are the most relevant ones (Ferracini et al. 2019). Currently, the mirids *Nesidiocoris tenuis* and *Macrolophus pygmaeus* represent the most extensively commercialized predators (Desneux et al. 2022).
Entomopathogenic fungi (EPF): *Beauveria bassiana* (Cordycipitaceae) and *Metarhizium anisopliae* (Clavicipitaceae) are the most commonly commercialized species and have shown strong suppression of *T. absoluta* under laboratory, greenhouse and open field conditions (Erasmus et al. 2021; Kabaale et al. 2022; Giannoulakis et al. 2023).
Entomopathogenic nematodes (EPN): *Heterorhabditis bacteriophora* (Heterorhabditidae), *Steinernema carpocapsae*, and *S. feltiae* (both Steinernematidae) effectively target *T. absoluta* at all stages, achieving high level control under laboratory, greenhouse and open field conditions (Sabino et al. 2019; El Aimani et al. 2021; Waweru et al. 2025).
Bacterial sprays: *Bacillus thuringiensis* subsp. *kurstaki* has been shown to be effective against *T. absoluta* under laboratory, greenhouse and open field conditions (Dammak et al. 2016; Abolghasemi et al. 2023). First-instar larvae are the most susceptible (González-Cabrera et al. 2011).
Viruses: Granuloviruses have shown great potential for controlling *T. absoluta* (Mariño & Rincon 2023) and the effectiveness of a commercial product (Tutavir©, Andermatt Biocontrol, 6146 Grossdietwil, Switzerland) has been demonstrated in large greenhouse trials (Koller et al. 2024).
Pheromones: Female sex pheromones have been used for mass trapping and mating disruption (Caparros Megido et al. 2013) and resulted in reduced pest populations and plant damage (Jallow et al. 2020; Zekeya et al. 2022). Parthenogenesis, where females produce viable eggs without mating, limits pheromone effectiveness (Erasmus et al. 2022).
Plant extracts: Extracts from various plants have shown adverse effects on *T. absoluta* under laboratory, greenhouse and open field conditions by deterring feeding, reducing mobility, causing mortality and oviposition inhibition and/or deterrence. These include neem, ginger, citrus, garlic, clove, basil, lemongrass, and tobacco (Ahmed et al. 2022; Ricupero et al. 2022; Zerkani et al. 2022).
Host plant resistance: Tomato plants can provide resistance against *T. absoluta* via trichomes, volatiles, and secondary metabolites by deterring female and larval settlement, negatively affecting survival, development, emergence and fecundity (Narváez Vásquez et al. 2025). Wild tomatoes have significant resistance traits (Zannou et al. 2025b).
Sterile Insect technique (SIT): SIT reduces pest populations by releasing sterile males, which mate with conspecific females and produce non-viable offspring. The feasibility of sterilizing *T. absoluta* males using X-rays has been demonstrated in laboratory (Cagnotti et al. 2012; Paladino et al. 2016).

2 Literature search, study selection and application of decision-making approach

2.1 Search, inclusion and exclusion criteria

We conducted a search in Web of Science Core Collection in mid-September 2022 using the string "*Tuta absoluta*" OR "*Phthorimaea absoluta*" and updated it weekly until mid-June 2025. By the final search date, we found 1,290 studies published from 1965 to mid-June 2025. We assessed the articles by analyzing titles and abstracts. The following publications/ studies were excluded: i) review papers, ii) studies on host range or biological performance of *T. absoluta*, iii) studies assessing only a single alternative control method, iv) studies involving chemical insecticides, v) studies that tested combinations including methods not directly aimed at pest control such as fertilization, companion plants or food sprays, and vi) studies involving biotechnology methods relying on advanced molecular or genetic interventions (e.g., the use of RNA interference (RNAi). Only studies testing binary combinations of alternative methods, resulting in 91 publications, were chosen for further consideration. Inclusion was based on the following four criteria: (1) *T. absoluta* is the target pest, (2) the study involves combinations of two control methods/agents, (3) it is not a modelling or simulation study, (4) the experimental setups include at least one of the methods tested alone as a comparator. After applying these criteria, 66 research articles were retained for further analysis.

2.2 Data extraction

From the selected articles, we compiled a database summarizing information on the combinations tested (Data S1). This included the methods and agents involved, experimental conditions, experimental setups, comparators, assessed parameters and results. Each combination was treated as a separate experiment. When the same combination was tested in different experimental setups in a publication, or when the same alternative method or different strains of the same microorganism were used in different combinations, each case was counted as a distinct experiment. This resulted in a total of 154 experiments. Experimental conditions were classified into three scales: (1) "small scale", referring to trials conducted in laboratories or greenhouses under small confined conditions (e.g., clip cages, bug dorms); (2) "semi-field scale", referring to trials performed in large cages setups (with multiple tomato plants) in open fields or greenhouses; and (3) "commercial scale", referring to trials conducted in open fields or commercial greenhouses.

2.3 Result synthesis

The results were reported for each experiment and categorized into four levels depending on the parameters that were assessed (Data S1). 1) Behavior and performance: oviposition or attraction behavior, discrimination, sex ratio, longevity, developmental or oviposition period, emergence rates, fitness of the biocontrol agent (natural enemy size or conidial germination rate); 2) Natural enemy populations and their pest attack rates: parasitism or predation rates, abundance of natural enemies; 3) Effects on *T. absoluta* populations: offspring numbers, numbers of adults or larvae killed; 4) Crop damage and yield: fruit quality, fruit quantity, number of mines. For each level, the results were synthesized by assigning a positive, neutral or negative effect to reflect the impact of the combined methods on the assessed parameters. A "positive" effect was recorded when the combined treatment significantly improved a parameter compared to at least one of the individual methods tested alone. A "neutral" effect was recorded when there was no significant difference between the combined treatment and at least one of the individual methods tested alone. A "negative" effect was recorded when the combined treatment significantly impaired a parameter compared to at least one of the individual methods tested alone. In cases where both individual methods were tested alone as comparators, scores were allocated separately for each control method. Effects were determined from the observed outcomes for each parameter, rather than from the authors stated conclusions.

2.4 Data analysis

The effect allocation described above synthesized results at the assessed parameter level but does not provide an overview of how each combination interacted or contributed to pest control or how it influences the performance of biological control agents. Given the high heterogeneity of experimental conditions and reported outcomes, we applied a semiquantitative Multi-Criteria Decision-Making framework to integrate multiple parameters across combinations (Edwards 1977; Zardari et al. 2015; Siregar et al. 2017). This method is a structured decision-making approach used to evaluate IPM strategies based on multiple criteria by assigning weights to each criterion and scoring alternatives according to how well they meet those criteria (Byrne et al. 2025; Dias et al. 2025). In our case, each parameter assessed was assigned a weight (W) reflecting its relevance (Table S1) and an effect score (Es) indicating if the combination had a positive (+1), neutral (0) or negative (−1) effect on the parameter. The effect per parameter (E) (Data S1) was calculated as:

$$E = W \times Es$$

The total score for a given combination experiment was then calculated as:

$$\text{score} = \sum WEs$$

We did not use the score as a baseline to evaluate combinations, as strategies might look better simply because more parameters were measured, rather than because of better performance per parameter. Instead, the score was divided by the sum of weights giving the decision score according to the formula (Siregar et al. 2017):

$$\text{Decision score} = \frac{score}{\sum W}$$

This represents the average performance per unit of weight, i.e., how good the strategy is relative to the importance of what was measured. The formula is applied to evaluate combinations based on experimental condition, category of control methods, and specific taxon, substance or method (Data S2). Decision scores are classified as effective when greater than 0.2, neutral when between −0.2 and 0.2, and ineffective when less than −0.2 (Table S2). These thresholds were chosen as logical classification tools to clearly distinguish positive or negative outcomes from weak or inconsistent effects. Smaller thresholds would risk interpreting minor differences as meaningful, while larger thresholds would classify most combinations as neutral. Although alternative cut-offs could slightly modify categorical assignments, the selected values capture meaningful trends without overinterpreting minor variations. The resulting classifications should therefore be interpreted as structured syntheses rather than statistically inferred breakpoints.

Decision scores were visualized as a heatmap using R (version 4.4.1), while descriptive statistics and additional data visualizations were produced in Microsoft Excel.

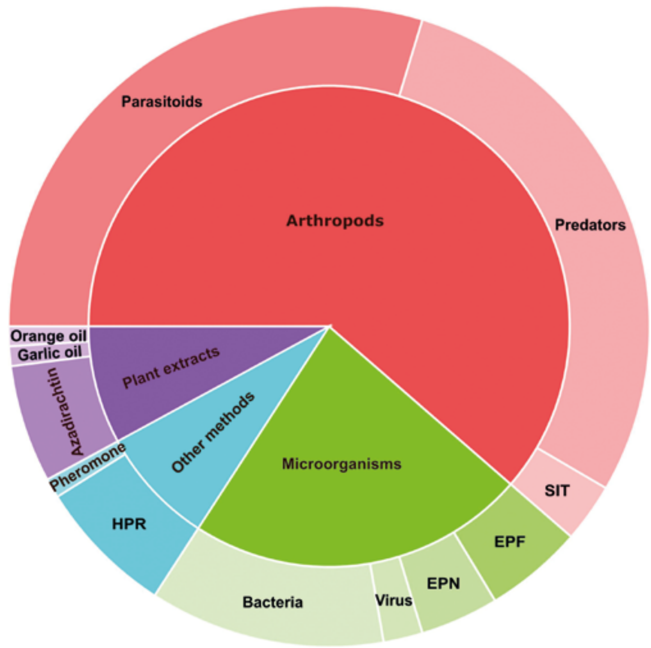

Fig. 1. Proportion of specific types of alternative control methods used in binary combinations against *T. absoluta*, as reported in the literature (n = 154 combination experiments from 66 articles) SIT = Sterile Insect Technique, EPN = Entomopathogenic nematodes, EPF = Entomopathogenic fungi, HPR = Host plant resistance.

3 Current evidence on the effectiveness of binary combinations of selected alternative methods against *T. absoluta*

3.1 Summary

A substantial number of 66 research articles reporting on two-method combinations against *T. absoluta* were published between 2000 and mid-2025, whereas no such studies were documented prior to 2000 (Data S1). Over half of the combination experiments involved arthropods (Fig. 1), mainly predatory mirids (*N. tenuis* and *M. pygmaeus*) and *Trichogramma* egg-parasitoids (*T. achaeae* and *T. brassicae*) (Fig. S1). Microorganisms were dominated by bacteria (Fig. S1; Fig. S2), with 85% of combination experiments using *B. thuringiensis* subsp. *kurstaki* (Fig. S2). Most combination experiments (79%) were conducted at a small scale, while only 11% and 10% were carried out under semi-field or commercial conditions, respectively. About 36% of the interactions were effective (Fig. 2).

3.2 General evidence-based evaluation of combined control methods

Many experiments investigated specific combinations of control methods, such as parasitoids with predators, bacteria or fungi, predators with host plant resistance or nematodes and plant extracts with bacteria. While high numbers of experiments might lead to the assumption that those combinations are particularly effective, the available data does not support this (Fig. 2). Some combinations that showed strong potential for *T. absoluta* control, according to the respective decision score, were explored in only a small number of experiments. These combinations included parasitoid-pheromone, predator-bacteria and predator-predator and plant extracts with either entomopathogenic fungi or nematodes. Some combinations, notably, predator-predator or combinations involving plant extracts and microorganisms consistently demonstrate high efficacy against *T. absoluta* (Fig. 2). In contrast, the combinations predator-plant resistance and parasitoid-plant extract show clear incompatibilities. Furthermore, some promising combinations that have not yet been explored against *T. absoluta* include viruses integrated with either plant extracts such as azadirachtin or with bacteria, as well as entomopathogenic nematodes combined with parasitoids, all of which have shown efficacy against other lepidopteran pests (Dáder et al. 2020; García-Munguía et al. 2025).

3.3 Specific evaluation of combined control methods

3.3.1 Arthropod-arthropod interactions

While the overall score of combinations of parasitoids and predators indicates a neutral effect, combinations of two predators are in most cases effective and combinations of two parasitoids are in most cases ineffective (Fig. 2). However, species-specific interactions influenced the outcomes (Fig.

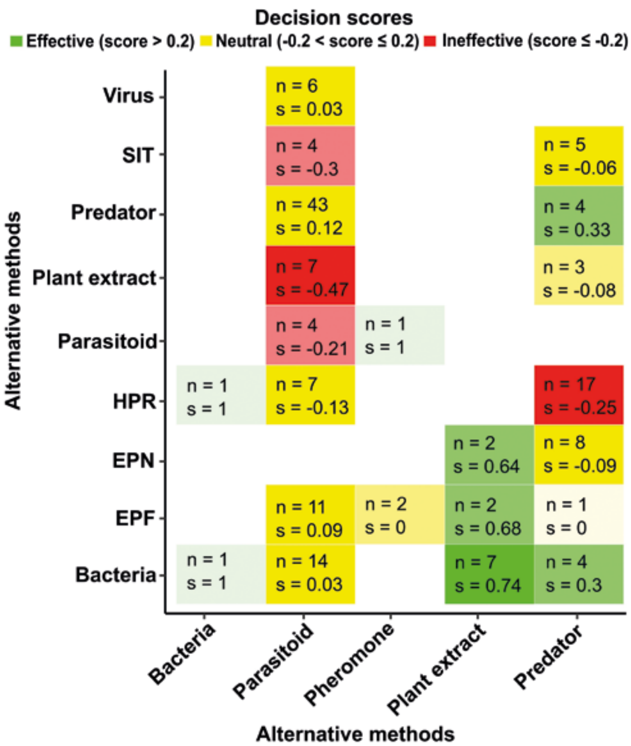

Fig. 2. Level of effectiveness of binary combinations using specific types of alternative control methods against *T. absoluta*, based on data from 154 experiments reported in 66 articles. n = number of combination experiments, s = decision score. Colors indicate the effectiveness of binary combinations based on calculated decision scores. Color transparency reflects the number of combination experiments, with fully opaque representing five or more experiments, moderately transparent representing two to four experiments, and highly transparent representing a single experiment. SIT = Sterile Insect Technique, EPN = Entomopathogenic nematodes, EPF = Entomopathogenic fungi, HPR = Host plant resistance.

S3). For instance, the most effective combinations included *Trichogramma achaeae* Nagaraja and Nagarkatti and *Macrolophus pygmaeus* (Rambur) or *Nesidiocoris tenuis* (Reuter) (Chailleux et al. 2013a; 2013b; Cabello et al. 2015; Borges et al. 2023; Pasquale et al. 2024), *T. brassicae* Bezdenko and *Nabis pseudoferus* Remane (Nabidae) (Mohammadpour et al. 2019; 2020; 2021), *T. pretiosum* Riley and *M. basicornis* (Stal) (Bueno et al. 2023a; 2023b; Van Lenteren et al. 2023), *Necremnus tutae* (Ribes & Bernardo) and *N. tenuis* (Calvo et al. 2016; Adams et al. 2024), *M. pygmaeus* and *Dicyphus errans* (Wolf) (Miridae) (Konan et al. 2023), as well as *Dineulophus phthorimaeae* (de Santis) (Eulophidae) and *Pseudapanteles dignus* (Muesebeck) (Braconidae) (Luna et al. 2010; Savino et al. 2017). Although, such combinations may lead to intraguild predation or kleptoparasitism, potentially compromising parasitoid and predator populations, this did not appear to reduce the efficacy of controlling *T. absoluta*. Negative interactions occur mainly at small scales, particularly for combinations such as *Bracon nigricans* Szépligeti (Braconidae) with *Dolichogenidea gelechiidivoris* Marsch (Braconidae) (Mama Sambo et al. 2023), *N. tenuis* or *Stenomesius japonicus* (Ashmead) (Eulophidae) paired with *M. pygmaeus* (Chailleux et al. 2014; Naselli et al. 2017; Duarte Martínez et al. 2022; Dervisoglou et al. 2022). However, *N. tutae* paired with *N. tenuis* (Calvo et al. 2016), and *M. pygmaeus* paired with *S. japonicus, D. errans* or *N. tenuis* proved effective at semi-field and commercial scales (Table 2; Data S1) (Calvo et al. 2016; Chailleux et al. 2017; Yao et al. 2022; Konan et al. 2023). Larger and more complex ecosystems, offering greater host availability may reduce competition and allow arthropod natural enemy species to coexist and interact. In some cases, the ability of certain species to discriminate parasitized hosts may further reduce interference and enhance their combined effectiveness (Chailleux et al. 2013a; Savino et al. 2017; Mohammadpour et al. 2020; 2021; Jamwal et al. 2022; Bueno et al. 2023a; Van Lenteren et al. 2023). The strength of the interactions is determined by factors such as release order, timing and frequence of releases of natural enemies. Whether combining parasitoids with predators or predators with other predators, earlier release of one predator before pest infestation, followed by the later release of the second species, generally provides more effective pest control. For example, eight weekly releases of *T. pretiosum* pupae combined with three releases of *M. pygmaeus* at the time of *T. absoluta* arrival (Bueno et al. 2023b), or thirty weekly releases of *T. brassicae* females combined with one release of *N. tenuis* applied either ten days before or after *T. absoluta* infestation (Mirhosseini et al. 2019a; 2019b), are recommended for effective pest control and improved yield. Similarly, first releasing 10 or 15 *M. pyg-*

Table 2. Levels of effectiveness of binary combinations of alternative methods against *T. absoluta* assessed at two different scales. n = number of combination experiments, green = effective, yellow = neutral, red = ineffective. SIT = Sterile Insect Technique, PhopGV = *P. operculella* granulovirus, Bt-kurstaki = *B. thuringiensis* subsp. *kurstaki*.

Method 1	Method 2	Small scale	Semi-field	Commercial scale
Azadirachtin	*Bt-kurstaki*	4		2
D. phthorimaeae	*P. dignus*	2		1
M. pygmaeus	*N. tenuis*	2		1
N. tutae	*N. tenuis*	2		1
N. tutae	PhopGV	2	1	
Pheromone	*M. anisopliae*	1	1	
S. japonicus	*M. pygmaeus*	4	1	
T. achaeae	*M. pygmaeus*	6	3	
T. achaeae	*N. tenuis*	1	1	
T. brassicae	*B-kurstaki*		1	1
T. cucurbitaceus	SIT	4	1	
T. pretiosum	*M. basicornis*	5	1	

maeus per plant, followed by the release of five *D. errans* seven days later, resulted in more effective reduction of *T. absoluta* larvae than *M. pygmaeus* alone (Konan et al. 2023). For the combination of larval parasitoids, competition is reduced when species attack different larval stages. In such cases, it is generally suggested to release parasitoids that attack early stages first, because the host discrimination ability of the later-acting species may help to reduce the negative interference. This pattern is illustrated by *D. phthorimaeae*, which prefers *P. dignus* unparasitized larvae under small scale conditions (Savino et al. 2017). The same trend appears to occur under commercial-scale conditions, where parasitism rates are similar when the species act alone or in competition (Luna et al. 2010).

3.3.2 Arthropod-microorganism interactions

For the overall scores, none of the combinations involving arthropod natural enemies and microorganisms (virus, bacteria, EPF and EPN) resulted ineffective (Fig. 2). However, evaluating the individual interspecific interactions revealed variable outcomes depending on the timing of application and dosage (Fig. S4). Combinations such as *D. gelechiidivoris* with *Metarhizium anisopliae* (Metchnikoff) or *Bacillus thuringiensis* Berliner subsp. *kurstaki*, and *Steinernema carpocapsae* (Weiser) with either *N. tenuis* or *M. basicornis* resulted in reduced parasitism and parasitoid emergence, fungal infection of parasitoid offspring or increased predator mortality in small-scale trials (Mama Sambo et al. 2022a; Kamou et al. 2024; Urbaneja-Bernat et al. 2025). These negative effects were primarily due to the direct application of microorganisms on the arthropods, which increases their exposure to harmful effects and consequently discourages the simultaneous use of natural enemies and microorganisms. Nevertheless, when natural enemy releases are delayed for some days after microbial treatment, this mitigates the adverse effects and certain microorganisms demonstrated potential compatibility with key natural enemies (Alsaedi et al. 2017; Guevara et al. 2020; Nozad-Bonab et al. 2021; Gonthier et al. 2023a; Koller et al. 2024; Lisi et al. 2024; Munawar et al. 2025). Proper timing transformed a negative interaction between *D. gelichiidivoris* and *M. anisopliae* into an effective one reducing *T. absoluta* infestation (Mama Sambo et al. 2022a). Moreover, with appropriately timed exposure, natural enemies may experience reduced host quality due to microbial infection, but not necessarily to a degree that compromises their development or performance (Biondi et al. 2013; Gonthier et al. 2023a; Mama Sambo et al. 2022a; Urbaneja-Bernat et al. 2025). A right time application of *N. tenuis* and *B. thuringiensis* subsp. *kurstaki* significantly reduced pest infestation and resulted in a higher weight of fruits compared to the predator alone under semi-field conditions (Mollá et al. 2011). However, timely deployment of this same combination (Jallow et al. 2022), along *T. brassicae* with *B. thuringiensis* subsp. *kurstaki* in both semi-field and commercial conditions (Alsaedi et al. 2017; Jamshidnia et al. 2018), and of *Elachertus inunctus* Nees (Eulophidae) with *B. thuringiensis* subsp. *kurstaki* at the commercial scale (Yarahmadi et al. 2018), did not result in differences in parasitism, pest reduction, fruit damage or crop yield compared to the biocontrol agents applied alone. This highlights the challenges to obtain effective outcomes as a result of many influencing factors. While proper timing appears to be important when combining the application of microorganisms and arthropod natural enemies, simultaneous application may also be effective particularly when a sublethal dose of the microorganism is used (Nozad-Bonab et al. 2021).

3.3.3 Arthropod-other methods interactions

When natural enemies were used in combination with other methods including pheromones, plant extracts, resistant cultivars or SIT, only a few effective combinations were observed, and these were supported only by limited experimental evidence (Fig. S5). For example, the combined use of *Trichogrammatoidea bactrae* (Subba Rao and Kaur) (Trichogrammatidae) and pheromones resulted in significant pest suppression and increased tomato yield compared to pheromones alone at a commercial scale (Goda et al. 2015). In contrast, combinations of natural enemies with plant extracts, such as azadirachtin, orange or garlic oil were largely ineffective, reducing predation, parasitism, and the natural enemy's development across all scales, thereby compromising pest control (Biondi et al. 2013; Yarahmadi et al. 2018; Soares et al. 2019; Lisi et al. 2024). These compounds may exert direct toxic effects on natural enemies or interfere with their host or prey-finding abilities. While application timing appears not to be important, a reduction in the plant extract dose may offer a pathway to mitigate non-target effects (Soares et al. 2019). Further research is needed to optimize compatibility and maximize the effectiveness of combining arthropod natural enemies with plant extracts.

The outcomes of combining host plant resistance with natural enemies highlight the relevance of resistance traits in biological control (Fig. S5). Strong plant resistance characteristics, such as abundant glandular trichomes found in wild species or some domesticated cultivars, negatively affected the performance of mirids, egg and larval parasitoids in small scale conditions (Gonçalves-Gervàsio et al. 2000; Bottega et al. 2017; Ghorbani et al. 2019; Guruswamy et al. 2023; Zannou et al. 2025a). These resistance traits form a strong barrier that physically hinders the settlement of natural enemies and reduces their ability to locate or attack hosts. In contrast, resistant cultivars with fewer glandular trichomes supported the activity of these natural enemies in small scales (Bueno et al. 2019; Guruswamy et al. 2023; Zannou et al. 2025a), with combinations such as *T. brassicae* and a resistant domesticated cultivar achieving effective pest suppression and reduced crop damage at commercial scale (Saeidi & Raeesi 2021). This indicates the imperative for breeders to preserve the necessary genetic diversity in tomato cultivars to sustain the efficacy of biological control agents.

According to the current evidence, the combined use of SIT and natural enemies seems species-specific and depends on which sex of *T. absoluta* is subjected to sterilization (Fig. S5) (Cagnotti et al. 2016a; 2016b; 2021; Candás et al. 2024). Eggs from irradiated females remained suitable for both *Tupiocoris cucurbitaceus* (Spinola) (Miridae) and *T. pretiosum* (Cagnotti et al. 2016a; 2016b), allowing feeding and parasitism. In contrast, *T. nerudai* (Pintureau and Gerding) showed reduced parasitism and fewer offspring on eggs from irradiated females, suggesting higher sensitivity to irradiation effects (Cagnotti et al. 2016a). Moreover, *T. cucurbitaceus* reproduced less when feeding on eggs from females mated with irradiated males, likely due to reduced egg quality (Cagnotti et al. 2021). Nonetheless, under semi-field conditions, infestations still declined, indicating complementary pest suppression (Candás et al. 2024). Frequent releases of natural enemies may compensate for these limitations, particularly under inundative or augmentative strategies aimed at rapid population suppression. In this context, combining natural enemies with SIT is advantageous, as the two approaches are inversely density-dependent, biocontrol is more effective at high densities, whereas SIT performs best at low densities (Kapranas et al. 2022).

3.3.4 Other combinations

Of the evaluated methods not involving arthropods, the vast majority were scored effective, with no combination classified as ineffective (Fig. S6). All combinations containing *B. thuringiensis* subsp. *kurstaki* demonstrated efficacy at small and commercial scales (Bue et al. 2012; Birgücü et al. 2014; Amizadeh et al. 2015; Abd El-Ghany et al. 2016; Jallow et al. 2019; Khatami et al. 2023) (Data S1). Notably, azadirachtin and *B. thuringiensis* subsp. *kurstaki* combinations consistently yielded high performance at both small and commercial scales (Bue et al. 2012) (Table 2). *Bacillus thuringiensis* subsp. *kurstaki* combined with either resistant cultivar, *B. thuringiensis* subsp. *entomocidus* or garlic oil resulted in increased pest suppression under small scale conditions (Abd El-Ghany et al. 2016; Khatami et al. 2023; Ochieng et al. 2024). Similarly, azadirachtin integrated with *B. bassiana* or *S. feltiae* (Filipjev) enhanced pest suppression, reduced damage, and increased yield under commercial scale (Mutegi et al. 2018; Amizadeh et al. 2019; Jallow et al. 2019) (Data S1). Further, pheromones had a neutral effect on the germination and viability of *M. anisopliae*, indicating that they can be safely combined with the fungus in combined control strategies and used for monitoring purposes without compromising fungal efficacy (Akutse et al. 2020). The published experiments evaluating these combinations do not suggest that the interactions are driven by factors such as the order of application, or the dosage of plant extracts or microorganisms. However, the number of studies assessing these combinations is limited. When mass-trapping or host plant resistance is integrated with microorganisms or plant extracts, or when two bacteria such as *B. thuringiensis* subsp. *kurstaki* and *B. thuringiensis* subsp. *entomocidus* are used, adherence to recommended dosages is essential (Abd El-Ghany et al. 2016; Akutse et al. 2020; Khatami et al. 2023). Further, the recommended dose of azadirachtin or garlic oil can be applied together with *B. thuringiensis* subsp. *kurstaki, Beauveria bassiana* (Balsamo), or *S. karii* Poinar without affecting the viability, persistence, or efficacy of the microorganisms (Bue et al. 2012; Birgücü et al. 2014; Mutegi et al. 2018; Jallow et al. 2019; Ochieng et al. 2024).

However, when integrating bacteria with azadirachtin, the LC_{25} of bacteria can be applied simultaneously with the recommended dose of azadirachtin (Amizadeh et al. 2015) and when combining azadirachtin with *S. feltiae*, it is recommended to apply azadirachtin at least 24 h after nematode application, regardless of the dose to minimize negative interactions (Amizadeh et al. 2019). Therefore, the use of azadirachtin with microorganisms indicates effective pest control when correctly applied. These results suggest the prioritization of microbial biocontrol agents and plant extracts in IPM programs against *T. absoluta*, while encouraging further confirmation of effective control using less frequently studied combinations.

3.4 Limitations of the review

This review adapted a weighting-based decision-making tool to evaluate studies on combinations of alternative methods for controlling *T. absoluta*. The method uses a structured approach that integrates weighted parameters into a single decision score, enabling direct comparison and classification of integrated strategies from heterogenous experimental conditions and reported results. However, the method has certain limitations. First, the assignment of weights to parameters or decision thresholds is subjective and may not align with priorities in different management contexts (Steiro et al. 2020; Byrne et al. 2025). Second, the use of the same weights across different experimental conditions may also hide context-specific differences. For instance, the same weight was given to parameters investigated under controlled and uncontrolled conditions. Third, some combinations were assessed in small-scale studies, which typically measure low-weight parameters rather than key outcomes like pest suppression or yield. Even with normalization (score divided by $\sum W$) (Siregar et al. 2017), decision scores can be misleading, reflecting parameter selection rather than actual performance, as seen for combinations tested in single experiments with scores of −1, 0, or 1. Additionally, although scores are classified as overall effective or ineffective, these categories do not represent absolute outcomes, as individual studies may still report variability among the combinations evaluated. Despite these limitations, the scoring approach remains a valuable and practical tool for synthesizing complex data into a simplified note, facilitating the evaluation of IPM strategies (Steiro et al. 2020; Byrne et al. 2025; Dias et al. 2025). A further limitation is that combinations of chemical insecticides and alternative methods were not considered, although such combinations may be compatible for controlling *T. absoluta* (Sabino et al. 2019; Wangari Nderitu et al. 2020). The present study focused on the contribution of combinations of alternative control methods and on the need to improve their application, given that chemical insecticides generally exert greater negative effects on ecosystems than the alternatives reviewed (Guedes et al. 2026).

3.5 Research gaps, outlook and conclusions

We synthesized a sizable number of studies on binary combinations of selected alternative methods to chemical insecticides with outcomes varying from being promising to unsatisfactory. Despite the extensive research, several important gaps remain, which limit the development and implementation of effective and sustainable control strategies. Most current knowledge is derived from small scale studies, which are useful to understand the mechanisms of pest control methods and their interactions (Calisi & Bentley 2009). However, they do not fully capture the complexity of field environments, where various biotic and abiotic factors influence the pest dynamics, as well as the efficacy of the control methods (Deguine et al. 2021). For instance, only 19% of combined strategies for managing *T. absoluta* were first evaluated at small- or semi-field scale and subsequently evaluated at a commercial scale (Table 2). Yet, for those studies all combinations maintained or even improved their effectiveness at commercial scale compared to the smaller scale trials (Table 2). This supports the hypothesis that integrated strategies that perform well at confined scales can retain their effectiveness under real farm conditions, highlighting the importance of field-level validation (Han et al. 2024). A further constraint is the lack of replicated trials and direct comparisons between combined methods. Additionally, the lack of technical and cost-efficacy analyses in greenhouse and on farm studies poses challenges for farmers considering adoption. Without comprehensive evidence, farmers may feel uncertain or pessimistic about integrated approaches as compared to chemical insecticides (Deguine et al. 2021). These two key gaps may delay IPM adoption, thereby causing farmers to miss out on alternatives for *T. absoluta* management. Thus, future research should prioritize trials at commercial scale (in open fields or greenhouses) that incorporate ecological complexity, controls where agents and substances are applied individually, along with economic evaluations which are key for growers. Although these assessments require significant human and financial investments, and often produce variable results, these efforts are essential to bridge the gap between research and practice. In this context, mathematical modeling of alternative combinations against *T. absoluta* could provide valuable insights, particularly where empirical commercial-scale data are limited (Rubio et al. 2022; Gonthier et al. 2023b).

For wide-scale adoption, further studies are also needed for combinations that require little technical expertise, such as plant extracts or mass-trapping integrated with microorganisms. For the most studied combinations, such as arthropod-arthropod interactions, future investigations should prioritize defining the densities of organisms involved, the order and frequency of their release, and the effects of these factors on pest populations, damage and yield. This is particularly relevant for short-term control through inundative or augmentative release. Besides binary combinations that directly target the pest, comprehensive IPM frameworks also include indirect and system level strategies. While beyond the scope of this review, further promising control options may be pointed out when analyzing those strategies in more detail. For example, it has been demonstrated that natural enemy efficacy can further be improved by enhancing their recruitment and retention. This includes habitat manipulation such as introducing companion plants (e.g., Sesame *Sesamum indicum* L.) (Konan et al. 2021), the provision of plant-derived food sources such as floral nectar, honeydew or plant guttation (Urbaneja-Bernat et al. 2024; Syropoulou et al. 2025), but also the application of phytohormones, such as Methyl Jasmonate (Strapasson et al. 2014; Weber et al. 2023). The combination of resistant cultivars with biological control agents also offers potential for effective management of *T. absoluta*. Breeding efforts should focus on developing cultivars that not only express resistance traits against *T. absoluta* but also support and enhance the performance of associated biocontrol agents. Conducting ecologically realistic trials, rigorous economic assessments and the development of context-specific integrated approaches is critical to advancing the effective implementation and broader adoption of sustainable IPM strategies against *T. absoluta*.

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Fig. S1–S6; Table S1, S2.