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Review

Managing thrips in strawberries: How effective are insecticide-free options? A *meta*-analysis

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HIGHLIGHTS

- Identification of effective methods for thrips management in strawberry crops.
- More than half of the studies focused on *Frankliniella occidentalis*.
- Biological control agents were as effective as insecticides.
- Treatment efficacy is highly dependent on site-specific factors.
- Plant resistance and host management are promising new areas for thrips control.

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ABSTRACT

Thrips are major pests in strawberry crops, with control becoming complex due to increasing temperatures, the banning of certain pesticides and growing insecticide resistance. As a global synthesis is lacking, we aimed to: list the interventions tested on strawberries; compare their effectiveness; and identify promising new strategies and research gaps. We conducted a systematic literature review, using Web of Science on October 18, 2024. We included studies monitoring thrips population or damage in strawberries with management interventions. Fifty-nine papers met our criteria, thirty-six of which included a negative control and were included in a *meta*-analysis. *Frankliniella occidentalis* (n = 30) and *Scirtothrips dorsalis* (n = 10) were the most studied species. Biocontrol agents and insecticides were the most common interventions, each assessed in 39 % and 47 % of studies, respectively. Predators were the most promising alternative to insecticides and the effects of 19 such species were observed. *Neoseiulus cucumeris*, *Orius laevigatus* and *Transeius montdorensis* were the most extensively studied. Across studies, predators reduced thrips populations by 51 % to 78 %, compared with 56 % to 79 % using insecticides. Variability between study sites was more significant than between treatments highlighting the importance of other factors, such as climate, not considered in this analysis in the method's effectiveness. Using tolerant varieties and mass trapping reduced thrips populations by an average of 65 % and 68 %, respectively. However further research is needed. Recent studies also highlighted the importance of early-season population dynamics and surrounding flora on thrips management. Despite progress, more research is required to optimize these strategies.

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1. Introduction

Strawberries are a well-known fruit grown worldwide (FAOSTAT, 2022). Although there are other species of strawberries (such as *Fragaria vesca*), most strawberry crops in the world are *F.* × *ananassa* Duchesne (Rosaceae; Husaini and Zaki, 2016). This crop is grown in temperate and some subtropical regions (FAOSTAT, 2022). The main strawberry-producing countries are China, the United States, Turkey, Australia, Mexico, and Egypt (FAOSTAT, 2022). It is a crop with significant turnover per unit area and fruit quality is essential for sales and producer income (Melis et al., 2021).

Pests, such as thrips, are one of the major threats to strawberry fruit quality and yield (Strzyzewski et al., 2021; Lahiri et al., 2022). There are many species of thrips, all from the family Thripidae (Thysanoptera), of which a small proportion are problematic on crops (Moritz et al., 2001). This order is divided into two suborders: Tubulifera and Terebantia which includes several families containing herbivorous thrips such as the Aeolothripidae, the Heterothripidae, the Melanthripidae, the Phlaeothripidae and especially the Thripidae, which include the species commonly considered problematic on strawberry plants (Mound et al., 2018). Thrips are hemimetabolous insects with an egg, four instars, and an adult stage (Mound et al., 2018). For the suborder Tubulifera, there is an additional instar (Mound et al., 2018). On strawberries, the main thrips pests are currently *Frankliniella occidentalis* Pergande, *F. intonsa* (Trybom), *Thrips tabaci* Lindeman, *Scirtothrips dorsalis*, *F. bispinosa* Morgan, *T. palmi* Karny, and *F. schultzei* (Cluever et al., 2016; van Kruistum and den Belder, 2016; Renkema et al., 2020). The amount of injury caused by a species seems to depend on the region, for example, *S. dorsalis* is mainly a problem in the USA (Lahiri and Yambisa, 2021; Montemayor et al., 2022). However, it is difficult to distinguish between species, especially at the larval stage (González-Zamora and Garcia-Marí, 2003; Atakan et al., 2016; van Kruistum and den Belder, 2016). Although thrips are not a single group, they are often considered to be, without distinction of species or even genus. This happens in practice, in the field for growers, and in scientific studies (e.g. Shahzad et al., 2018).

By feeding on plants, thrips adults and larvae cause damage to flowers, fruits, and leaves (Koike et al., 2009; Strzyzewski et al., 2021). Thrips are rasping suckers and are vectors of viruses (Moyer et al., 2010). Strawberries are not the only plants affected by thrips. The genera *Thrips* and *Frankliniella* are polyphagous, and cause problems in vegetable crops (e.g. leeks, onions), fruit crops (e.g. melons, cucumbers, peppers) and ornamentals (e.g. chrysanthemums) among others (Mainali and Lim, 2010; Shakya et al., 2010; Sampson and Kirk, 2013). Population management with synthetic insecticides has often been seen as a solution yet can result in the development of resistance in insect populations given their short life cycle (Weiss et al., 2009). For example, resistant populations of *F. occidentalis* exist on all continents and for at least nine of the chemical classes (IRAC, 2016). It is vital to find alternatives to synthetic insecticides or to increase the diversity of available products. One of the advantages of insecticides is that they are fast-acting and curative (Broughton and Herron, 2007; Cluever et al., 2016; Renkema et al., 2020). However, their impact on the environment and health and their poor degradability mean that we need to limit their use (Bai and Ogbourne, 2016; Wang et al., 2022a; Araújo et al., 2023). Non-synthetic insecticides are an alternative, but these can also cause the development of resistance (Siegwart et al., 2015; Thomas and Read, 2007), negative impacts on the environment or on health (Holmes et al., 1998) and their effectiveness is often limited and less known (Renkema et al., 2020). These non-synthetic insecticides include living micro-organisms, which are emerging as a promising biological control strategy against thrips in crops and other strawberry pests (D'Ambrosio et al., 2020; Sabbahi et al., 2008; Wu et al., 2018a,). These organisms act by competing for resources, by producing toxic compounds, by direct predation or by activating plant defence mechanisms (Helyer and Brobyn, 1992; Mantzoukas et al., 2022; Wu et al., 2018a; Zulaika et al., 2024). Endophytes, which reside in plant tissues without causing damage, also sometimes have a beneficial impact on the growth of their hosts while having a negative impact on pest and disease populations (Mantzoukas et al., 2022; Barasa et al., 2024). However, little research has been conducted on the impact of these products on thrips populations, especially in strawberry crops (Canassa et al., 2020; Zahn and Morse, 2013).

Predators can be used to control thrips by releasing them or by promoting existing populations (Barbar et al., 2024; Mouratidis et al., 2022; Vervoort et al., 2017; Wang et al., 2022b). However, this may not be sufficient if the thrips population is too large or if the damage occurs outside the activity period of the predator (Lahiri et al., 2022). The use of predators is less straightforward, as numerous parameters influence their effectiveness. These include the predator population size (Weintraub et al., 2011; Saito and Buitenhuis, 2024), interaction with insecticides used (Lin et al., 2021; Busuulwa et al., 2024), temperature (Ren et al., 2022), humidity (Shipp et al., 1996), the presence of other food sources (Shakya et al., 2009) or other predators (Shakya et al., 2010; Saito and Buitenhuis, 2024). In addition, the difficulty of establishing and maintaining a population for some of these species remains a major barrier to their use (van Kruistum and den Belder, 2016). Closed systems are better suited to the introduction of natural predators, but open-field systems incorporate impact from the existing populations (Tuovinen and Lindqvist, 2014). Living organisms also pose certain health and ecological problems, whether they be predators or micro-organisms (Holmes et al., 1998; Sakai et al., 2015; Loomans, 2021).

A literature review on available control methods against *S. dorsalis* was published in 2013 but did not focus on strawberries (Kumar and Kakkar, 2013). Another narrative review on arthropod management in strawberry crops has a paragraph on thrips (Lahiri et al., 2022). Other narrative reviews deal with general thrips management methods, without focusing on strawberry crops (Mouden et al., 2017; Reitz et al., 2020). A systematic review specifically on thrips in strawberries has not been conducted. By doing so, we provide a complete picture of the state of knowledge concerning means and methods of managing thrips populations in strawberries worldwide. The objectives were: (i) to identify which methodologies have been used to assess the impact of an intervention on the thrips population or strawberries damage; (ii) to list the tools and methods tested in these experiments and their efficacy; (iii) to identify the best alternatives to the existing conventional control systems; and (iv) to identify the best avenues for future development and innovation.

2. Materials and methods

2.1. Data inclusion criteria

We performed a literature search in Web of Science with the following keywords on 18 October 2024: ("*thrip*" OR "*Frankliniella*" OR "Thysanoptera") AND ("strawberr*" OR "*Fragaria*") in the topic field. The search was performed without restriction of document type, time, or language with the keywords.

2.2. Data exclusion criteria

We evaluated the obtained articles by following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method (Page et al., 2021). We only included articles presenting information from at least one study revealing a relation between any factor and thrips population and/or damage. We retained studies conducted on whole strawberry plants or on part of the plants when the strawberry plants themselves were the factor being evaluated. We also excluded review articles, articles from conference proceedings covering the same information as another study already in the selection and all articles considered off-topic (Fig. 1). This selection was made by the same person for all the reports and no automatization tool was used.

The first screening resulted in 172 publications. Sixty were excluded

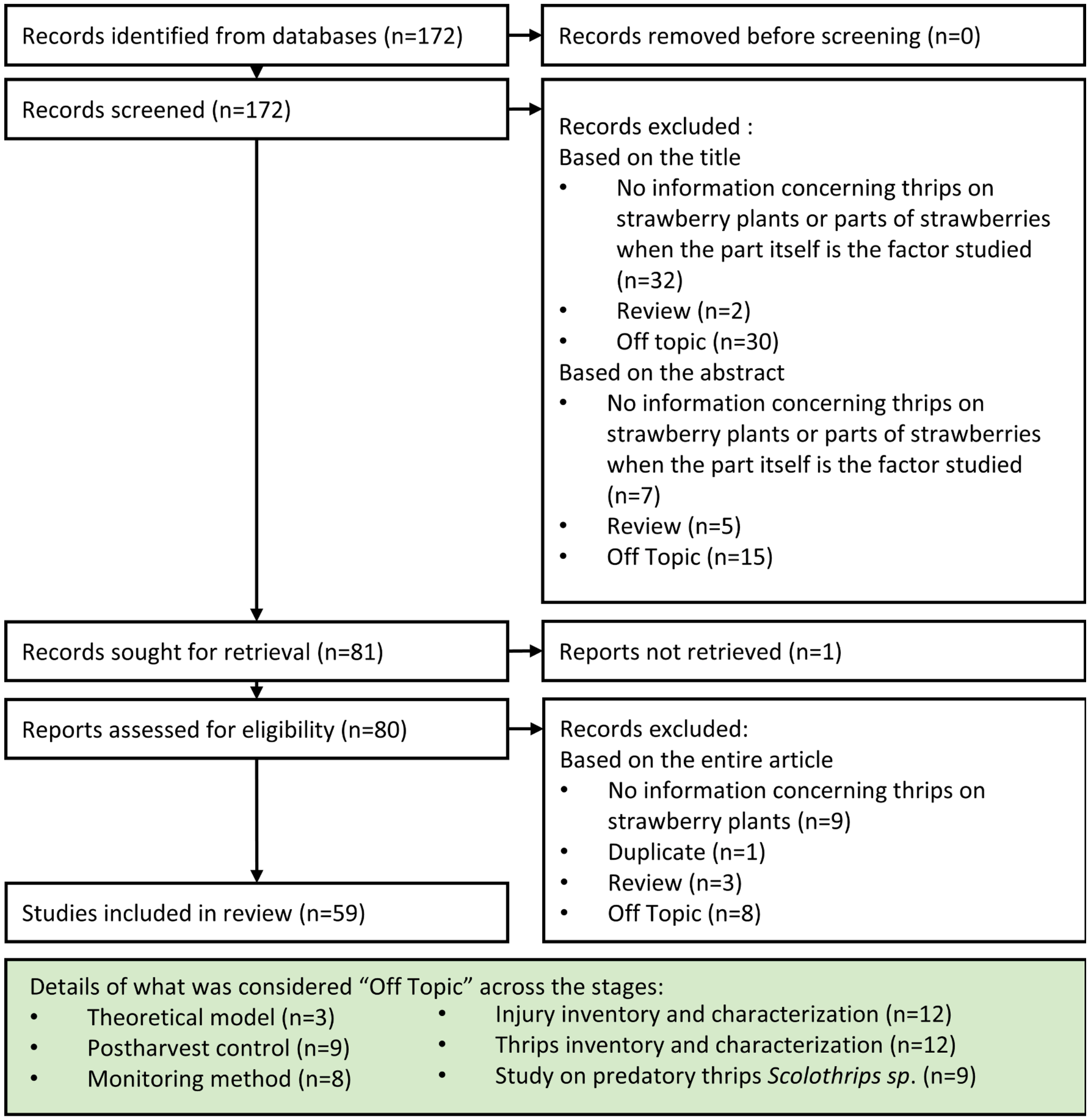

Fig. 1. PRISMA flow diagram.

because they were either reviews (n = 10), did not include any result concerning the thrips and/or the strawberries (n = 49), or were duplicates from another study (n = 1). One was not retrieved and 53 were off topic. That is: all post-harvest treatments (n = 9), articles on auxiliary thrips *Scolothrips* sp. (n = 9), thrips inventories and characterization (n = 12), injury inventories and characterization (n = 12), monitoring method (n = 8), or theoretical models (n = 3). Finally, information from 59 articles was compiled in this review (Fig. 1).

2.3. Data extraction

We manually extracted and used the following data where available: (1) location of the experiment; (2) year of publication; (3) study design (experimental or observational); (4) parameter(s) evaluated; (5) response variable; (6) number of replicates (7) origin of thrips (introduced or native); (8) thrips species monitored; (9) method of determining thrips; (10) strawberry variety; (11) mean effects; and (12) standard deviations. Data (5), (11) and (12) were extracted for both the treated and control groups only when the response variables were: (i) a direct measure of the thrips population (count of individuals), or (ii) the following indirect measure of thrips population: damage score; % fruit or leaf surface damaged; % or fruits or leaves.

For values presented in a time series with more than three points, if there was a trend, the maximum and minimum values were considered, or, if there was no trend, the median of the temporal values was considered. When a result summarizing other results was available, only the overall value was included. In the case of apparent error (e.g. mean not within one standard deviation) the data for the modality were excluded from the review.

2.4. Handling missing data

There were no missing data, i.e. data not available in the article and/or in the online supplementary material, for parameters (1) to (6). The origin of the thrips (parameter 7) was considered native by default if no introduction was mentioned. For parameters (8) to (10) we reported the missing information. In three articles, parameter (11) mean effects were not available or were incomplete. For one of these, it was possible to recover them from the principal authors, the remaining two were removed from analysis. When the standard deviation was not available, it was first deduced from other available measures (standard errors or confidence intervals) or requested from the principal authors. For four articles, the standard deviation could not be recovered and was therefore imputed (see below).

2.5. Study classification and evaluation

The studies were classified into five categories: 1) insecticidal substances (except living organisms), 2) biocontrol agents (BCA), 3) varietal resistance, 4) traps, and a category grouping subjects covered by fewer than four articles; 5) other. The risk of bias in the studies was assessed by noting whether treatments had been randomized, or whether a negative control was present, whether results were exhaustively reported (no selective reporting bias) and by the presence of details of the financing of the study. Any financial or material donation from a company producing the tested treatment was classified as a motivated donation.

2.6. Statistical analysis

All studies were included in the qualitative part of this review. Only those with a negative control and mean effects (n = 36) were included in the quantitative part of the analysis. The imputation of the missing SD's was done before further data transformation and using a linear model with mean and number of replicates as explanatory variables.

In the case of studies with multiple trials, each of them was individually integrated in our *meta*-analysis. The standardized mean difference (SMD, Hedges' g) between treatment and control was used as effect size for the comparison and the statistical analysis was done with linear mixed effect models using the restricted maximum likelihood estimators (REML). To consider the impact of using multiple trials from the same author(s) we integrated the first authors as a random factor. For the

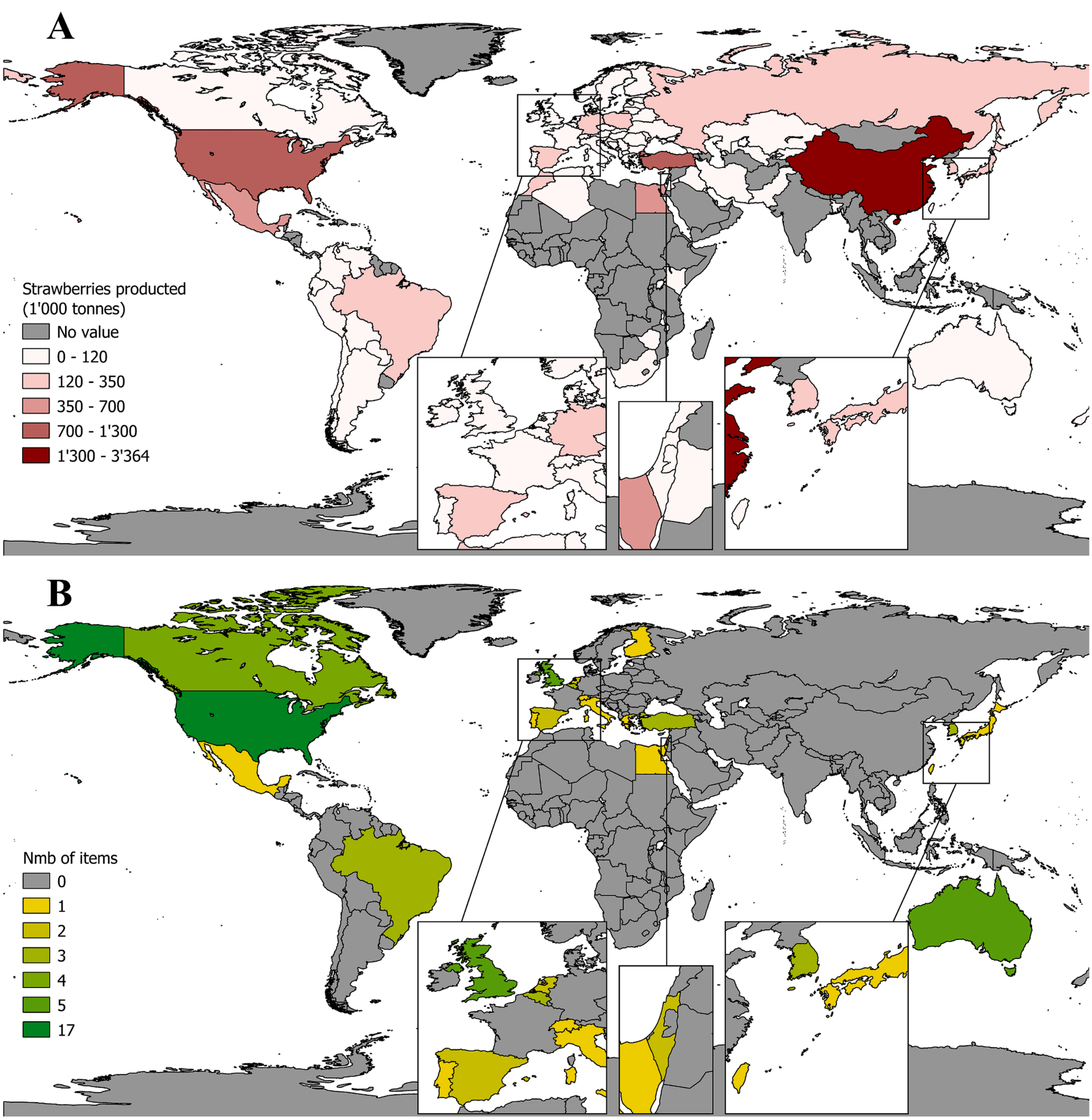

Fig. 2. A) Strawberry production in 1000 tonnes per country for the year 2022 (FAOSTAT 2022), B) Number of items per country among the papers used for this article (n = 59).

studies where multiple measurements were available for one experiment (e.g. number of adults and number of larvae) a mean main effect was calculated using the method for composite data explained in Mengersen et al. (2017). The impact of the sampling methodologies was assessed by adding those as moderators into the models but allowing for differences in residual heterogeneity. The factors observed were the type of response variable (direct or indirect), the organ observed (leaf, fruit, flower and plant) and the stage of thrips development observed (larvae, adult or both). The same method was used to compare treatments. All analyses were performed using R Statistical Software version 4.2.2 (R Core Team, 2022). The *meta*-analysis and production of the graphs was done with the package "metafor" (Viechtbauer, 2010). A sensibility analysis was performed to assess the impact of the transformation for composite data used and influence tests were used to detect studies introducing extra residual heterogeneity into the model and to identify their impact on the conclusions. The risk of publication bias was assessed using funnels plots and models including the sampling variance as moderator.

3. Results and discussion

3.1. Contexts and methodologies

Of the 59 studies, 29 % were from Europe (n = 17), 37 % from north America (n = 22), 10 % from Oceania (n = 6), 10 % from the Middle East (n = 6), 9 % from east Asia (n = 5) and 5 % from South America (n = 3, Fig. 2). All articles were published between 1993 and 2024. The quartile boundaries (Q1, Q2 and Q3) were 2009.5, 2016 and 2020.5 respectively. There was a peak in research in 2010 and there has been an increase in papers in the last 9 years (Fig. 3).

Three quarters of studies focused on thrips from the genus *Frankliniella* (n = 42, Fig. 4). The species *F. occidentalis* was the most studied (n = 30 as primary species). *Scirtothrips dorsalis* was the second most studied species, as the main species in ten studies. Other species that were given a prominent place in at least one study were *Thrips major*, *T. fuscipennis*, *T. tabaci*, *Heliothrips haemorrhoidalis*, *F. bispinosa* and *F. intonsa, F. tritici*, *S. inermis*. Most papers contained results on a native thrips population (n = 42). Nineteen studies resulted from at least one experiment on a pest population introduced on plants in a controlled system. Only Renkema et al. (2020) deliberately propagated a native population to assure the homogeneity of the populations. In 18 studies using native populations, the authors gave no indication of the method used to identify thrips species. In these studies, the authors reported results for *Frankliniella spp*. (n = 2), *F. occidentalis* (n = 7), *S. dorsalis* (n = 1), *F. intonsa (n = 1)*, *Thrips imaginis* (n = 1), *T. tabaci* (n = 1), and seven used the term "thrips" without defining the species. The other studies identified the thrips using a microscope (n = 20), unclear identification in laboratory (n = 1), identification in field (n = 3) and fruit damage identification (n = 1). The determination keys used were specified in only nine studies. These were Cook et al. (2002), Broughton and Herron (2007), Lim and Mainali (2009), Nondillo et al. (2009), Mainali and Lim (2010), Sampson et al. (2021), Canovas et al. (2023a,b), Kaur et al. (2024) who used Stannard (1968), Palmer et al. (1992), Denmark et al. (1996), Mound and Kibby (1998), Moritz et al. (2001), Vierbergen et al. (2010), Hoddle et al. (2012), Cluever and Smith (2017), and Mound et al. (2018).

Most of the studies presented the results of experimental trials (n = 48) and 11 studies were observational. Most trials were conducted either in open-field conditions (52 %) or in greenhouses (32 %). The others were conducted in tunnels (13 %) or climatic rooms (3 %). Fifty-five different varieties were used (not including seven unknowns and one *Fragaria x ananassa*). The most frequently used were Camarosa (9 %), Albion (7 %), Florida Radiance (7 %) and Camino Real (6 %). Five studies did not specify which variety was used and two reported 'confidential' varieties. In seven studies, the authors noted only indirect indicators of the presence of thrips, 40 studies presented only the results of direct thrips counts, seven studies presented both types of observations, and one did not specify the monitoring method. Of the studies that measured the direct presence of thrips, eight presented results only for the presence of adult stages, two only for the presence of juvenile stages, 16 presented results for both stages and 21 made no distinction (Fig. 5). Only one presented males and females separately. Although fruit and flowers were the most frequently observed, the observational units varied greatly between studies (Fig. 5).

Of the 59 studies selected, 23 presented results on insecticides, 28 on BCA (including 12 on both), five on varietal resistance and tolerance, and six on trapping. The other themes covered by four or fewer articles were the use of vacuums, elicitors, alarm pheromones, methods exploiting the photosensitivity of thrips and articles discussing the impact of the presence of another pest, other host plants in the vicinity, the border effect, overwintering, different fertilization and different soil covers on thrips populations and their damage (Fig. 6). There was no

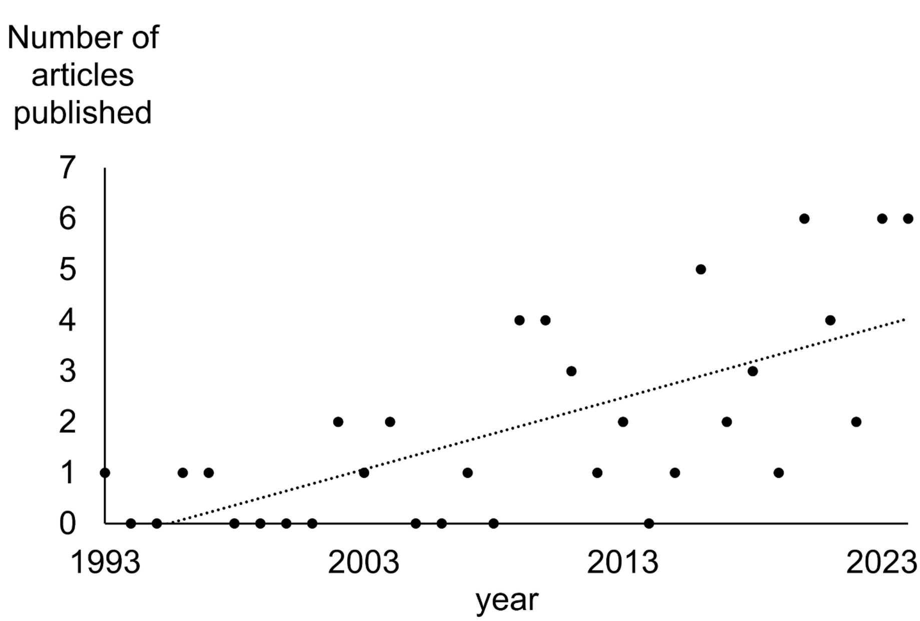

Fig. 3. Number of publications per year among the articles included in this literature review (n = 59).

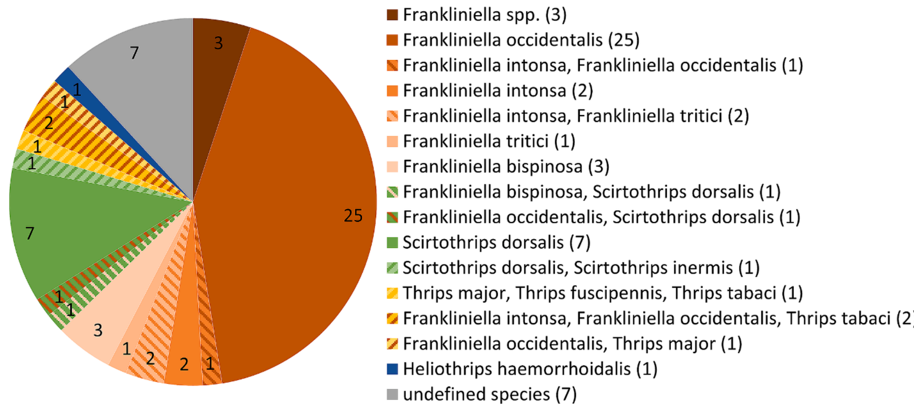

Fig. 4. Main thrips species studied in the trials (n = 59).

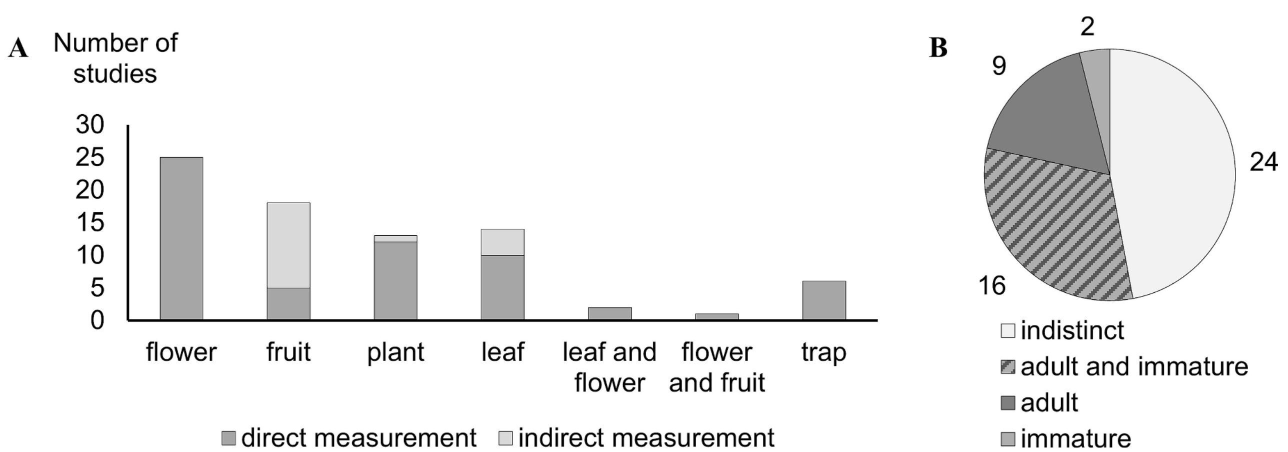

Fig. 5. A) Number of articles presenting results for each observation unit, the graph indicates whether the measurement made is a direct measurement of the presence of thrips or an indirect measurement (n = 59), B) Development stages of thrips observed and measured in studies making direct measurements of the thrips population (n = 51).

great variation in the quality (risk of bias) of the articles, depending on the subject covered (Fig. 6). The general quality of the studies was good. Few cases of selective reporting were observed. However, some information was not always provided: seven studies did not specify whether treatments were allocated in a randomized manner, and 14 did not provide any information about the funding of the trials, mainly in the case of those evaluating commercially available products or varieties. Of the ten studies that were funded at least in part by companies with commercial interests, eight had only partial financial support (and three received only the intervention method). One study had apparent errors in its results, so the results in question were not included in the *meta*-analysis, and another gave no information about the protocol followed, so this study was excluded from the *meta*-analysis,

3.2. Insecticidal substances

There were 23 studies included in this category (Fig. 6). Thirty-six different insecticides were used in all the studies. Of these, 19 were used in a single study. The products whose efficacy was assessed the most were spinetoram and spinosad, two insecticides with the same mode of action (Fig. 7). This is partly because these two insecticides are often used as positive controls. Many of the tested insecticides were used in combination, and this was often the case for those classified as extracts with unknown or uncertain action mode (UNE). As it was not possible to ensure attribution of effects, these latter modalities could not be included in the *meta*-analysis. Fifty-four trials were included in the *meta*-analysis. Insecticides generally reduced thrip infection with a pooled SMD of −1.50 with a 95 % confidence interval (CI) of ± 0.69 (p-value $<$ 0.0001) and heterogeneity was very high with an I-squared statistic (I^2), which quantifies the percentage of total variation across studies that is due to heterogeneity rather than chance, of 70.4 % and a Q value of 148.42 (p-value $<$ 0.001). The results of the models by treatment are presented in Fig. 8 and details of the results by trial are available in supplementary material. The analysis confirms the efficacy of spinetoram in reducing thrip infection with a pooled overall effect of SMD −2.06 ± 0.73 (CI). However, another study showed the development of resistance to this insecticide in strawberry crops in the USA (Weiss et al., 2009). Despite a high average effect, the general efficacy of spinosad was not demonstrated by the analysis (SMD −2.77 ± 2.87 CI), the variability between studies observed for this treatment was very high (I2 90.5 %). For the other products tested, there were too few trials to allow robust conclusions. However, abamectin, analycarb, methomyl, chlorpyrifos, methamidophos, endosulfan, fipronil, abamectin, tolfenpyrad and cyantraniprole were effective. No significant effects of malathion, deltamethrin, acetamiprid, flupyradifurone, novaluron, extract of capsicum oleorecin and *Metarhizium robertsii* were reported. Substantial reduction of thrips pressure but inconsistent results were observed with bifenthrin and sulfoxaflor. The 17 other products could not be included in the analysis because we only had qualitative results for them, results with no negative control or only combined results with non-assignable effects. Mevinphos used with endosulfan was able to keep thrips below thresholds (Sterk and Meesters, 1997). Similar results were presented for spirodoclofen and thiacloprid combined together with abamectin (Melis et al., 2021). Acrinathrin showed similar results

Category	Study	In meta-analysis	Negative control	Mean effect available	SE available	Randomized design	No selective reporting	No interested funding	No other biais
insecticidal substances	Atakan et al. 2016	+	+	+	+	?	+	?	+
	Broughton and Herron 2007	+	+	+	+	+	+	+	+
	Cluever et al. 2016	+	+	+	+	+	+	+	+
	Cook et al. 2002	+	+	+	+	?	+	+	+
	Dara et al. 2018	+	+	+	+	+	+	-	+
	Lahiri et al. 2021	+	+	+	+	?	+	-	+
	Lahiri et al. 2024	+	+	+	+	+	+	+	+
	Melis et al. 2021	-	-	+	i	?	+	+	+
	Montemayor et al. 2022	+	+	+	+	+	+	+	+
	Panthi and Renkema 2020	+	+	+	+	+	+	?	+
	Panthi et al. 2024	+	+	+	+	+	+	+	+
	Price 1993	+	+	+	-	+	+	?	+
	Rahman et al. 2011a	+	+	+	+	+	+	?	+
	Rahman et al. 2011b	+	+	+	+	+	+	?	+
	Rahman et al. 2012	+	+	+	+	+	+	-	+
	Renkema et al. 2018	+	+	+	+	+	+	-	+
	Renkema et al. 2020	+	+	+	+	+	+	-	-
	Sterk and Meesters 1997	-	-	+	-	-	+	?	+
	Tescari et al. 2004	+	+	+	-	?	-	?	+
	Van Kruistum and Den Belder 2016	+	+	+	+	?	+	+	+
	Weiss et al. 2009	-	-	+	-	-	-	?	+
	Wold and Hutchison 2003	+	+	+	+	+	+	+	+
	Yarpuz-Bozdogan et al. 2017	+	+	+	-	+	+	+	+
Biocontrol agents	Albendin et al. 2015	+	+	+	+	+	+	-	+
	Atakan 2011	-	-	+	+	-	+	?	+
	Canassa et al. 2020	+	+	+	+	+	+	+	+
	Coates et al. 2023	-	-	+	+	?	+	+	+
	Dara et al. 2018	+	+	+	+	+	+	-	+
	Fitzgerald and Jay 2013	+	+	+	-	+	+	+	+
	Frescata and Mexia 1996	+	+	+	+	+	+	+	+
	Lahiri et al. 2021	+	+	+	+	?	+	-	+
	Lahiri et al. 2024	+	+	+	+	+	+	+	+
	Melis et al. 2021	-	-	+	i	?	+	+	+
	Mantzoukas et al. 2022	+	+	+	+	+	+	+	+
	Mouratidis et al. 2023	+	+	+	+	+	+	+	+
	Rahman et al. 2011a	+	+	+	+	+	+	?	+
	Rahman et al. 2011b	+	+	+	+	+	+	?	+
	Rahman et al. 2012	+	+	+	+	+	+	-	+
	Renkema et al. 2018	+	+	+	+	+	+	-	+
	Renkema et al. 2020	+	+	+	+	+	+	-	-
	Saito and Buitenhuis 2024	-	-	+	+	+	+	-	+
	Sampson and Kirk 2016	+	+	+	+	+	+	?	+
	Shakya et al. 2009	+	+	+	+	+	+	+	+
	Shakya et al. 2010	+	+	+	+	?	+	+	+
	Sterk and Meesters 1997	-	-	+	-	-	+	?	+
	Takeda 2002	-	-	-	-	+	+	+	+
	Tuan et al. 2016	-	+	-	-	+	-	?	+
	Tuovinen and Lindqvist 2010	+	+	+	+	+	+	+	+
	Van Kruistum and Den Belder 2016	+	+	+	+	?	+	-	+
	Vervoort et al. 2017	+	+	+	+	?	-	+	+
	Weiss et al. 2009	-	-	+	-	-	-	?	+
varietal resistance	Abdelmaksoud et al. 2020	-	i	+	+	+	+	?	+
	De Souza et al. 2022	-	i	+	+	+	+	+	+
	Mouden et al. 2021	-	i	+	+	+	+	+	+
	Rahman et al. 2010	-	i	+	+	+	+	?	+
	Rahman et al. 2011a	-	i	+	+	+	+	?	+
traps	Lim and Mainali 2009	+	+	+	+	+	+	+	+
	Mainali and Lim 2010	-	i	+	+	+	+	+	+
	Matos and Obrycki 2004	-	i	+	+	+	+	+	+
	Panthi et al. 2021	-	i	+	+	-	?	+	+
	Sampson and Kirk 2013	+	+	+	+	+	+	-	+
	Shin et al. 2020	-	i	+	-	-	+	+	+
other	Canovas et al. 2023a	-	-	+	+	-	+	+	+
	Canovas et al. 2023b	-	-	+	+	-	+	+	+
	Cook et al. 2002	+	+	+	+	?	+	+	+
	Dara et al. 2018	+	+	+	+	+	+	-	+
	Fitzgerald and Jay 2013	+	+	+	-	+	+	+	+
	Fountain et al. 2022	+	+	+	+	+	+	-	+
	Kaur et al. 2024	-	-	+	+	-	+	+	+
	Koller et al. 2024	+	+	+	+	+	+	+	+
	Matos and Obrycki 2004	-	i	+	+	-	+	+	+
	Mérida-Torres et al. 2024	-	i	+	+	+	+	?	+
	Montemayor et al. 2022	+	+	+	+	+	+	+	+
	Mouden et al. 2021	+	+	+	+	+	+	+	+
	Nondillo et al. 2009	-	i	+	+	+	+	+	+
	Sampson et al. 2019	-	-	+	+	+	+	+	+
	Shahzad et al. 2018	-	+	-	-	+	-	?	-
	Tokaji and Nakao 2020	-	-	+	i	-	+	+	+
	Tuovinen and Lindqvist 2010	+	+	+	+	+	+	+	+
	Van Kruistum and Den Belder 2016	-	-	+	+	?	+	-	+

Fig. 6. List of reports included in this review by category and assessment of their methodology and risk of bias. The values "+" indicate explicit compliance with the condition, "-" explicit non-compliance with the condition, "?" unavailable information and "i" an irrelevant point. Other biases" include the visible presence of errors in the results or an incomplete protocol (n = 59). (See above-mentioned references for further information.)

to spinosad in one study (Tescari et al., 2004). The combination of chlorantraniliprole with thiamethoxam reduced thrips pressure at the beginning of the season (Renkema et al., 2020). Under certain conditions, heat killed *Burkholderia spp*. resulted in thrips population reductions comparable to those observed with conventional insecticides but was less effective in limiting fruit damage. Flonicamid gave good results in combination with applications of acetamiprid (Renkema et al., 2020). No significant effect on thrips populations was observed for essential oils (garlic, canola, geraniol, peppermint, rosemary, neem), potassium salts of fatty acids, pyrethrins or azadirachtin (Dara et al., 2018; Renkema et al., 2020).

The I^2 value for the general model was 70 %. We observed that 52 % could be associated with between-author variability and 18 % with between-treatment variability within author's work. No significant difference (p-value = 0.75) could be demonstrated between studies directly measuring thrips populations and those indirectly measuring thrips populations, but a slight trend was observed: on average, studies giving indirect measurement results (SMD −1.34 ± 1.34 SE) were correlated with less marked effects than those giving direct measurement (SMD 1.70 ± 0.53 SE). No bias seemed to have been introduced by the organ observed, and the very slight and non-significant trends observed can be explained by the direct or indirect population measurement parameter. No influence of insect development stage was observed. The sensitivity analysis showed very low sensitivity of the results to the transformation of the main effects calculated using the method for composite data, regardless of the correlation coefficient used (supplementary material). There were no influential studies in the general model. One study was influential in the spinetoram model (Panthi and Renkema, 2020) but had only a slight impact on the final result, which did not change the conclusions. Two studies were influential in the spinosad model (Tescari et al., 2004; Atakan et al., 2016). Without these two studies, the effect of spinosad significantly excluded the null hypothesis (SMD −3.26 ± 0.39 SE). A publication bias was detected for the general model (p-value = <.0001), idem for the spinetoram model, disappearing when excluding the influential study (Panthi and Renkema, 2020). No publication bias was detected for the spinosad model (p-value = 0.14), but the number of studies was very limited to ensure sufficient power for the test (funnel plots in supplementary materials). Despite the risk posed by these biases, and in view of the conclusions, the scale of the effects observed, the quality of the studies included in the *meta*-analysis and the non-quantitative observations presented in the other studies, the conclusions were robust to small changes.

Insecticides were the most effective tools among those with proven and confirmed results. These results are in line with the state of research in other crops and the use observed in practice (Kumar and Kakkar, 2013; Mouden et al., 2017; Reitz et al., 2020). Yet some of the synthetic insecticides presented in this study are no longer authorized. Those most commonly used today are spinosad and abamectin. Unsurprisingly, this study confirms their effectiveness. However, many cases of insecticide resistance developing in thrips populations (particularly *F. occidentalis*) have been reported and announced, and most of the major classes of insecticides currently in use are affected (Gao et al., 2021; IRAC, 2016). Management of these populations therefore depends on the development of resistance detection methods and the integration of other control methods into management strategies (Gao et al., 2012; Mocchetti et al., 2023). Spinosad, pyrethrins, azadirachtin and, in general, all products categorized as UNE by the IRAC are of organic origin and are therefore often (with a few exceptions) authorized for use in organic farming. We note, however, that the efficacy of products in this last category is limited and that the conditions required for these treatments to work properly have yet to be explored. These results are confirmed in certain reviews (Kumar and Kakkar, 2013). However, in the literature some products are presented as more effective than what has been observed; for example, for deltametrin (Mouden et al., 2017) or azadirachtin (Lahiri et al., 2022). These differences may be due to the lack of a systematic review protocol in the other studies, which take less

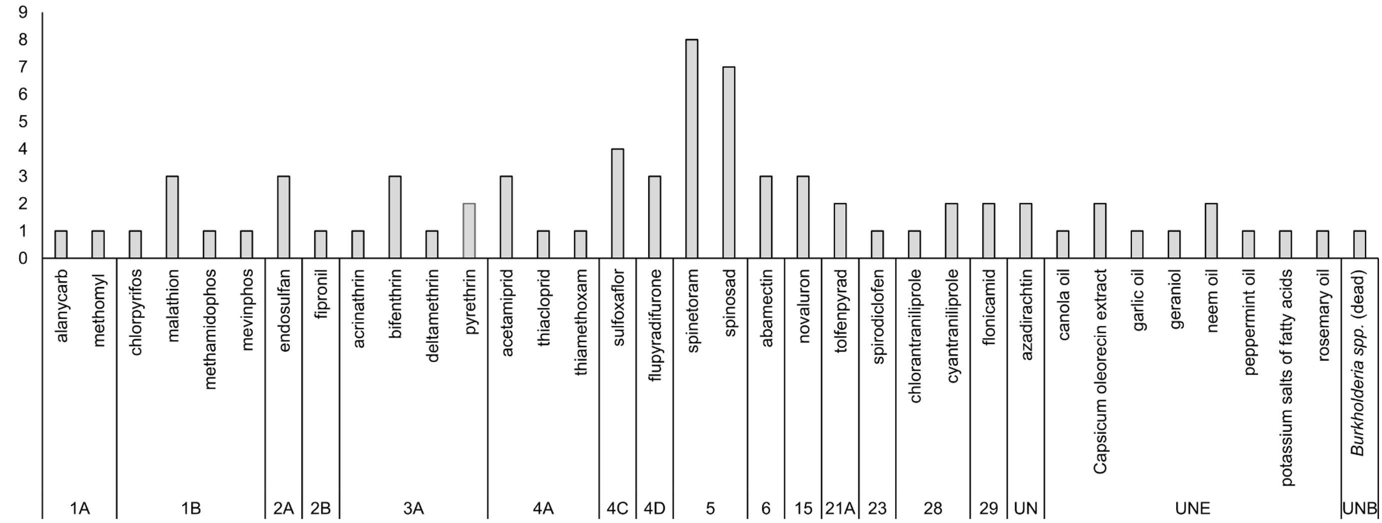

Fig. 7. List of insecticides observed in the studies and number of studies evaluating them. The second x axis categorizes the products according to their mode of action based on the Insecticide Resistance Action Committee classification (Sparks and Nauen 2015, n = 23).

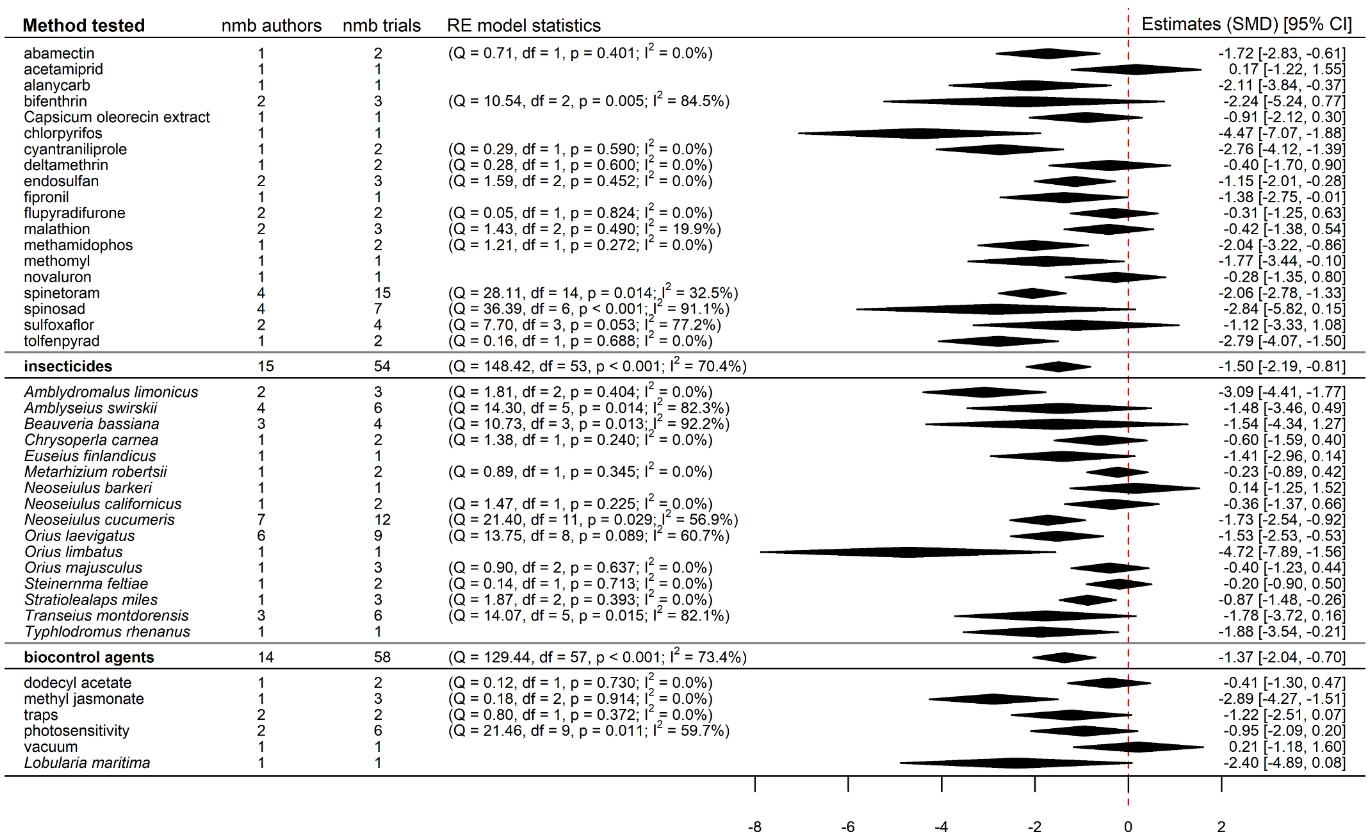

Fig. 8. Forest plot summarizing the models expressed in Standardized Mean Difference, calculated via linear mixed effect models using the restricted maximum likelihood estimators and evaluating the impact of the presence of a management tool compared with a negative control. BCA considered as insecticides by the IRAC were only represented in the insecticides category (Sparks and Nauen 2015, n = 36, see supplementary material for the detailed results).

account of non-significant results. Our results generally showed a significant effect of insecticides. Spinetoram could be recommended as a control in the studies to enable better comparability, as its efficacy is one of the most certain and least variable.

3.3. Biocontrol agents

There were 28 studies included in this category (Fig. 6). Twenty-five different species were evaluated at least once in these studies. The vast majority were mites of the Phytoseiidae family and insects of the *Orius* genus. Only one nematode species was evaluated, as well as one bacterium and four fungi (Fig. 9). The *meta*-analysis included 58 different trials. Unsurprisingly, the result of the *meta*-analysis on all biocontrol agents rejected the null hypothesis ($p = 0.0001$) with a pooled SMD of -1.37 ± 0.67 (CI), showing a general effect of treatment/control agents on thrip reduction compared to no intervention. This corresponded to an

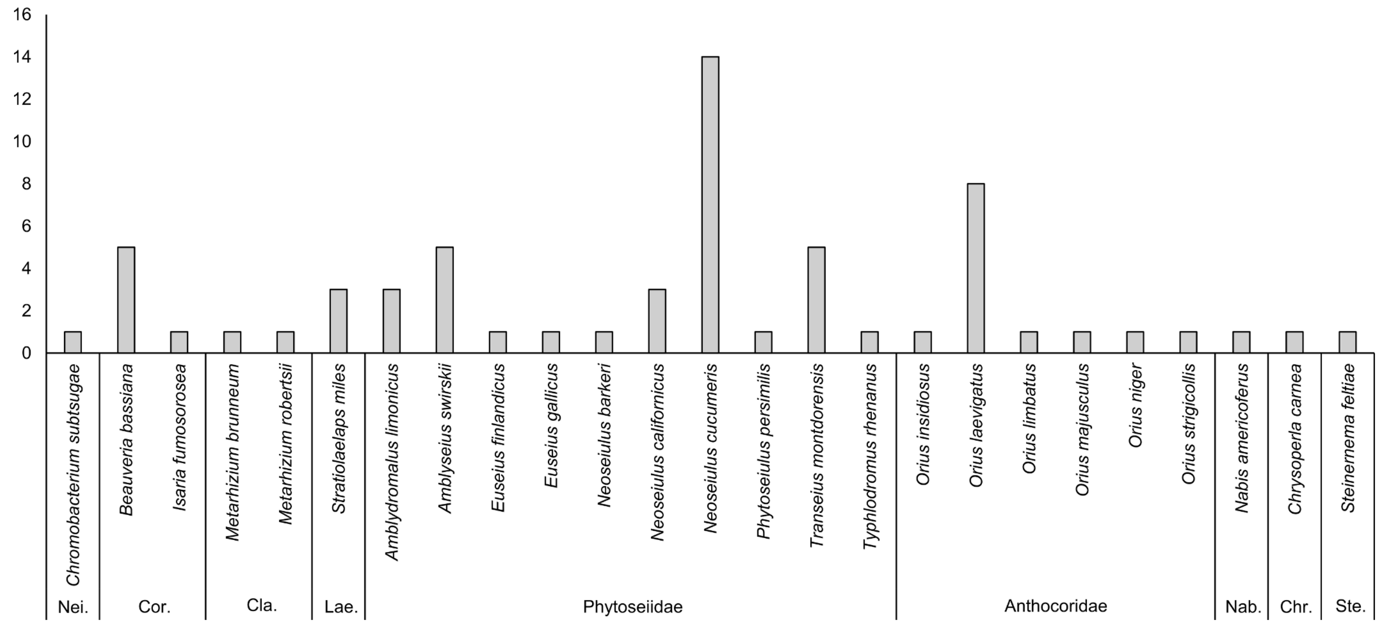

Fig. 9. List of species (predators and one parasite) observed in the studies and number of studies evaluating them. Species are classified by Family. Nei. = Neisseriaceae, Cor. = Cordycipitaceae, Cla. = Clavicipitaceae, Lae. = Laelapidae, Nab. = Nabidae, Chr. = Chrysopidae, Ste. = Steinernematidae (n = 28).

average reduction in thrips pressure of 51 % to 78 %. However, the Q pooled overall heterogeneity test indicated significant heterogeneity with a p-value of less than 0.001 and a very high I^2 of 73.4.8 %. Only *N. cucumeris*, *O. laevigatus, Amblyseius swirskii* and *T. montdorensis* were tested in more than five trials. The *meta*-analysis confirmed the efficacy of the first two (*O.l.* SMD 1.53 ± 1.00 CI and *N.c.* SMD 1.73 ± 0.81 CI) but, despite having a greater average effect, not for *A. swirskii* (SMD 1.78 ± 1.94) and not for the species *A. swirskii* (SMD 1.48 ± 1.98). This can be explained by the wide variability of results observed for those predators (I^2 = 82.1 %, and 82.3 %) and the limited number of studies (n = 3, and 4). For other BCA, the trial numbers were too small for robust conclusions, but the results still allowed for comparisons (Fig. 8; see supplementary information). The species *A. limonicus*, *A. swirskii*, *O. limbatus*, *S. miles* and *T. rhenanus* showed promising results for thrip reduction, whereas no effect could be demonstrated for *N. barkeri* and *S. feltiae*. Substantial reduction of thrips pressure but inconsistent results were observed with the entomopathogen, *Beauveria bassiana*. Once *B. bassiana* was applied by apivectoring, but despite good dispersal, no significant effect on thrips populations was observed compared with a control area, but this was probably due to the design of the experiment (Coates et al., 2023). *B. bassiana* was also applied by spraying (van Kruistum and den Belder, 2016) and by inoculation into plants, using its endophytic properties (Canassa et al, 2020; Mantzoukas et al., 2022). This may explain some of the inconsistency observed in the results, but it is not enough, as the greatest difference in results was observed between the two studies using inoculation into plants. Mantzoukas et al. (2022) observed the most promising results on thrips populations for this entomopathogen and observed a beneficial effect of the micro-organism on strawberry growth. For six predators, the bacterium and two fungi, only qualitative data or studies without controls were available: *E. gallicus* developed well in strawberry but showed no significant effect on thrips (Vervoort et al., 2017). During an observational study, *Orius niger* populations were strongly and positively correlated with thrips in strawberries crops, suggesting good potential for thrips control (Atakan, 2011). In a study with an accidental thrips infestation, an 80 % lower thrips population was observed with *O. strigicollis* compared to without predators (Tuan et al., 2016). *Orius insidiosus*, tested with other predators (*O. laevigatus* and *N. cucumeris*), kept thrips below thresholds compared to other crops in similar conditions but its individual effect was unclear (Sterk and Meesters, 1997). *Neoseiulus americoferus*, tested with *A. swirskii*, reduced significantly thrips populations (by around 60 %) compared to *A. swirskii* alone (Saito and Buitenhuis, 2024). *P. persimilis* alone and under conditions of heavy infestation, performed as well as when combined with either *N. californicus* or *A. swirskii* but significantly less effectively than when combined with *O. laevigatus* (Albendín et al., 2015). No significant effects on thrips populations were observed for *Chromobacterium subtsugae*, *Isaria fumosorosea* or *Metarhizium brunneum* (Dara et al., 2018; Renkema et al., 2020).

The I^2 value for the general model was 73.4 %. We observed that 72 % of variability can be associated with between-author variability and only 1.28 % with between-treatment variability within the authors' work. No significant difference (p-value = 0.51) could be demonstrated between studies directly measuring thrips populations and those indirectly measuring thrips populations. No bias seems to be introduced by the plant part observed nor the stage of development of the insects. The sensitivity analysis showed very low sensitivity of the results to the transformation of the main effects calculated using the method for composite data, regardless of the correlation coefficient used (sensitivity analysis in supplementary material). There were no influential studies in the general BCA and *N. cucumeris* models. However, two studies were influential in the *O. laevigatus* model (Vervoort et al., 2017; Mouratidis et al., 2023) but their exclusion of the analysis did not change the conclusion of no effect on thrips (SMD −0.86 ± 0.28 SE). In general, a publication bias was detected for all models run with a number of trials of 8 or more (p-value general model and *N.cucumeris* model = <.0001, *O. laevigatus* = 0.0006), potentially due to the use of a single literature search engine (funnel plots in supplementary materials). Despite the risk of bias, the scale of the effects observed, the quality of the studies included in the *meta*-analysis and the non-quantitative observations presented in the other studies, the conclusions seem robust.

Although the average effect of insecticides was slightly greater than that of BCA, the comparison between the two groups showed no significant difference between products and BCA (p-value = 0.82). The comparison between the main treatments (spinetoram, spinosad, *N. cucumeris* and *O. laevigatus*) also showed no significant difference. The p-value between *O. laevigatus* and *N. cucumeris* was 0.76, between *N. cucumeris* and spinosad 0.50 and between the insecticides 0.70. These measurements corresponded to the qualitative data observed: Melis et al., 2021 observed a milder effect of the IPM variant (*N. cucumeris*, *N. californicus* and *A. limonicus)* compared with the insecticide variant (abamectin, spirodoclofen and thiacloprid). The difference was most noticeable at the start of the season, outside the periods when predators were developing. In their study, Sterk and Meesters, 1997 observed similar results between their IPM and insecticide variants. These significant effects of predators against thrips were also very similar to what has been observed in other crops or in other summary works, although *Orius* spp. are often considered more promising than predatory mites (Mouden et al., 2017; Reitz et al., 2020), we observed the opposite trend. *Beauveria bassiana* is sometimes presented as more effective than it is (Mouden et al., 2017). These differences may be due to the lack of a systematic review protocol in the other studies, which take less account of non-significant results. Differences in efficacy between isolates were also important and may explain the differences in results observed between the studies in this systematic review (Francis and Manchegowda, 2023). To our knowledge, no other study has made a general comparison between insecticides and BCA on thrips. Our results strongly support the theory of a slightly lower but comparable efficacy of BCA compared to insecticides, which has often been reported in experiments comparing the two control types.

3.4. Varietal resistance

There were five studies included in this category (Fig. 6). All studies reported a significant impact of the strawberry variety on the thrips indicators. The mean difference in thrips population pressure between varieties was 40 %. The maximum differences between the most and least resistant varieties in each trial ranged from 86 % to 23 % reduction in thrips pressure, with an average of 65 % (Table 1). Only two studies checked which varietal characteristics were correlated with resistance. The positive correlation between the density of glandular trichomes and the reduction in thrips pressure was the only characteristic confirmed in two studies (Table 2). The study of Mouden et al. (2021) was the only one looking for variability in the effect of a treatment depending on the variety and did not discover any such interaction. Rahman et al., 2010 observed a significant difference between the number of eggs laid, larval mortality and the total duration of the thrips development cycle between treatments, varying from 14.6 ± 0.2 to 20.8 ± 0.9 eggs per leaf disc, from 31 ± 3.8 to 48.5 ± 2.5 % and from 11 ± 0.2 to 12 ± 0.2 days, respectively.

Varietal resistance has been little studied in strawberries but is already considered an important measure in other crops, and the results presented in this work support this trend. More fundamental research to understand the mechanisms behind these resistances, the classification of existing varieties according to their susceptibility and the development of resistant and commercially interesting varieties seem to be the next steps.

3.5. Traps

There were six studies included in this category (Fig. 6). Only two studies were included in the *meta*-analysis. We found no significant difference, probably due to the small number of studies (SMD −1.22 ± 0.66 SE, I^2 0 %) but the average effect, although not significant, was comparable to other insecticides or BCA tested (Fig. 8). The possibilities for optimization are well studied. Mainali and Lim (2010) observed that adding a black background to traps doubled the number of thrips caught per trap. Sampson and Kirk, 2013 observed that adding lures containing the *F. occidentalis* aggregation pheromone to traps seemed to increase their effectiveness (non-significant difference). Matos and Obrycki, 2004 observed contradictory results concerning the impact of the color (blue or yellow) on the thrips populations captured, one reason cited for these differences being the size of the thrips populations. Shin et al., 2020a observed that the three best placements for the traps were about 30 cm above the plants, at the height of the plants between the rows or 30 cm lower than the raised beds between the rows. Observations from Panthi et al., 2021 also demonstrated low mobility of these insects in

Table 1
Resistance of different strawberry varieties to thrips. When no mean for the whole study was available, the mean for the peak thrips population is shown. (n = 5).

Variety	response variable	mean	± SE[1]	signif.[4]	Source
Albion	# thrips per plant	5.6	± 0.9	b	Rahman et al. 2010 [2,3]
Camarosa		12.1	± 1.3	c	
Camino Real		2.4	± 0.6	a	
Camarosa	# adult *and larvae* thrips per plant	24.84	± 1.25	a	Rahman et al. 2011a
		29.13	*± 1.6*	*a*	
Albion		21.66	± 1.06	b	
		26.53	*± 1.3*	*b*	
Camino Real		19.89	± 0.94	c	
		22.41	*± 1.1*	*c*	
Albion	# thrips per plant	11.1	± 0.5	c	de Souza et al. 2022, first trial [2]
Aromas		24.8	± 0.5	a	
Camino Real		5.4	± 0.	d	
Monterey		16.8	± 0.5	b	
Portola		3.4	± 0.4	e	
San Andreas		11.3	± 0.5	c	
Albion	# thrips per plant	9	± 0.3	d	de Souza et al. 2022, second trial [2]
Aromas		14	± 0.3	a	
Camino Real		4.4	± 0.4	e	
Monterey		12.4	± 0.3	b	
Portola		2.2	± 0.4	f	
San Andreas		11	± 0.3	c	
Fortuna	# thrips per ten leaves	9.2	± 0.7	a	Abdelmaksoud et al. 2020, first trial
Sahary		8.9	± 0.3	ab	
Festival		8.5	± 0.4	ab	
Forintaris		7.9	± 0.6	b	
Red Merlin		6.7	± 0.4	c	
Winter Star		5.8	± 0.3	cd	
Winter Dawn		5.4	± 0.3	d	
Eliana		5.3	± 0.5	d	
Montary		3.9	± 0.3	e	
Florida		3.3	± 0.4	e	
Fortuna	# thrips per ten leaves	12.4	± 1.0	a	Abdelmaksoud et al. 2020, second trial
Festival		11.7	± 1.1	a	
Eliana		8.9	± 1.3	b	
Montary		2.4	± 0.3	c	

(*continued on next page*)

Table 1 (*continued*)

Variety	response variable	mean	± SE[1]	signif.[4]	Source
Florida		1.9	± 0.2	c	
Delizzimo	Thrips damage score (0 to 5)	2.32	± 0.29	a	Mouden et al. 2021 [2]
Rowena		1.19	± 0.21	b	
Elan		1.60	± 0.31	ab	

[1] Standard error.
[2] data measured directly on a graph.
[3] preference test: the varieties are in the same cage.
[4] Means followed by a different letter within the same trial are significantly different, $p < 0.05$. according to the authors.

strawberry crops. Traps are used more as a means of monitoring, but the current cost of these methods for control remains prohibitive, so it is rarely considered as a control method (Kumar and Kakkar, 2013; Lahiri et al., 2022). In cases where it has been used, optimization is necessary to minimise costs, as in other crops (Mouden et al., 2017; Reitz et al., 2020). Our results suggest good potential for the use of traps in thrips control but we underline the cost constraint.

3.6. Other factors

Other foci (n = 15) of thrips management were using methods such as a vacuum, pheromones, elicitors and methods exploiting photosensitivity (see supplementary information). The use of a vacuum does not seem effective (Fig. 8). The use of the alarm pheromone dodecyl acetate gave promising results and increased the efficacy of treatments with malathion, but not those with fipronil (Cook et al., 2002). The impressive efficacy of the elicitor, metyl-jasmonate, was particularly visible and significant on young plants (Mouden et al., 2021). The variability observed between the trials evaluating photosensitivity can be explained in part by the different methods used and the nature of the light: Fountain et al., 2022 used light-filtering screens whereas Montemayor et al. (2022) used active treatments. It seems that the latter are less effective on thrips. The presence of another pest in the crop had no impact on the thrips population for the species *Chaetosiphon fragaefolii* but increased thrips pressure with the species *Phytonemus pallidus*. The presence of another pest reduced the effectiveness of BCA (Tuovinen and Lindqvist, 2010; Fitzgerald and Jay, 2013). But thrips were more attracted to healthy plants or plants attacked by *Tetranychus urticae* than to those infested with other thrips (Mérida-Torres et al., 2024). *Frankliniella occidentalis* developed better in strawberry flowers than on leaflets, which suggests that control should focus on these organs (Nondillo et al., 2009). The impact of cold weather and winter population levels was also assessed. On outdoor crops in Iowa (USA), most thrips migrated onto the crops at the start of the season, while few overwintered in the soil on site (Matos and Obrycki, 2004). In strawberry crops, *S. dorsalis* thrips were not yet able to survive a winter in outdoor crops (Kochi, Japan; Tokaji and Shiro, 2020). In England, however, thrips overwinter in crops and that the number of thrips overwintering there has an impact on the following year's thrips population (Sampson and Kirk, 2013). Thrips overwinter in soil, but some forms also infest weeds throughout the year. These results were in line with what has been observed in Quebec (Canada), where many plants adjacent to crops serve as breeding grounds for thrips and the population in crops is higher at the edges of plots, close to these plants (Canovas et al., 2023a,b; Kaur et al., 2024). However, Koller et al. (2024), working in the Valais, Switzerland, observed fewer thrips on plants near flower strips, but the impact varied, depending on the species used in the floral enhancement. Only one study evaluated the impact of soil cover (van Kruistum and den Belder, 2016). A white plastic cover appeared to reduce the thrips population compared with straw (p-value 0.1), but this trend was not confirmed in other trials in the same paper. Shahzad et al., 2018 reported that a substantial 243 kg N/ha nitrogen fertilization reduced thrips pressure by 53 % compared to a 149 kg N/ha fertilization but no other studies on fertilizer influence were found. Among the other avenues of research,

Table 2
Link between the characteristics of the strawberry varieties studied (explanatory variables) and their resistance to thrips attack. When no average for the whole study was available, the average for the peak thrips population was used (n = 2).

Explanatory variable (x)	Response variable (Y)	equation	R^2	p-value	Varieties used	Source
non glandular trichome density ($/cm^2$)	mean thrips per ten leaves	$Y = -0.17x + 11.68$	0.72	< 0.001	Fortuna, Sahary Festival, Forintaris, Red Merlin, Winter Star, Winter Dawn, Eliana, Montary, Florida,	Abdelmaksoud et al. 2020
glandular trichome length (µm)		$Y = -0.7799x + 7.323$	0.01	n.s.[2]		[1]
glandular trichome density ($/cm^2$)		$Y = -0.7997x + 7.210$	0.54	< 0.05		[1]
thickness of leaflet (µm)		$Y = -0.075x + 16.65$	0.56	< 0.01		
leaf nitrogen content (mg/g)		$Y = -0.9282x + 8.486$	0.07	n.s.		[1]
leaf phosphorus content (mg/g)		$Y = 24.9x + 6.51$	0.41	< 0.05		
leaf potassium content (µEq/g)		$Y = -5.7x + 6.676$	0.44	< 0.05		
leaf total phenol content (µgGA/g)		$Y = -0.23x + 8.46$	0.77	< 0.05		
glandular trichome density ($/cm^2$)	mean thrips per plant in the month with the highest population	$Y = -1.999x + 27.26$	0.85	< 0.01	Albion, Aromas, Camino Real, Monterey, Portola, San Andreas	de Souza et al. 2022 [3] [1]
non glandular trichome density ($/cm^2$)		$Y = 2.346x + 1.321$	0.22	n.s.		[1]
glandular trichomes density ($/cm^2$)		$Y = -1.271x + 18.45$	0.98	< 0.001		[1]
non glandular trichomes density ($/cm^2$)		$Y = 2.049x - 0.6072$	0.48	n.s.		[1]

[1] equation not presented in the article but calculated.
[2] not significant (≥ 0.05).
[3] study conducted two times.

the most promising was the management of adjacent crops and companion plants, but the subject is very complex and methods for applying this knowledge in practice are still lacking.

3.7. Limitations

Our results can be applied to thrips control in all strawberry crops, but with some limitations. We presented generalized results for all species of thrips pests. Most thrips studied to date were flower thrips, but around 10 % of the studies were on leaf thrips. Although the biology of these species is similar, they have notable differences that could influence the results of certain management methods. This is also the case, but to a lesser extent, between species within the same group. Our results apply mainly to flower thrips (of the genera *Frankliniella* and *Thrips*). Consideration should also be given to thrips that are not harmful to crops or are even pest predators (e.g. *Aeolothirps* spp., *Haplothrips* spp., etc.), that may suffer from certain control methods. Our results can, to some extent, be extrapolated to other crops but must always be put into perspective with the implications that specific characteristics of strawberry crops imply (cultivation on substrate, flowering in cycles, bushy habit, etc.). The main methodological bias of this work is that only one database was screened. We assume that this is the main reason for the generally good quality of the studies, but also for the publication bias observed. We also noted that most of the high-producing countries are represented with the notable exception of China. Again, the choice of database is probably the reason for this bias as the pest is present in these countries (Wu et al., 2018b).

4. Conclusion

Thrips are one of the main pests in strawberry crops. Insecticides are often used to manage these populations, but the emergence of resistance, particularly for the species *F. occidentalis*, is prompting a search for alternatives. More than half of studies looking for methods of controlling these insects have focused on this species. The most common methodology was an experimental open field study, measuring the population of adult and juvenile thrips in strawberry flowers. However, there is much diversity in the methodologies used, and it would be useful to standardize procedures to make it easier to pool knowledge in the future. It appears that BCA (particularly *O. laevigatus* and *N. cucumeris)* are equivalent in effectiveness to the investigated insecticides (especially spinosad and spinetoram). Many other predators reduced the number of thrips, but the number of studies is limited. For most treatments, the variability of results is high and is mainly linked to agronomic and climatic factors. Better identification of these factors would enable control methods to be successful systematically. Varietal resistance is a promising solution, but more fundamental research and development of resistance varieties is needed before it can be applied in practice. The impact of traps often seems to be underestimated, but for this method to be applied on a large scale, we need to research and apply methods for optimizing their effectiveness. Future research should therefore focus on these latter points, as well as on applied methods for managing companion plants, or plants close to crops that have a major impact on infestations.

5. Availability of data and material

Any information relating to the study that is not included in the supplementary material or in the article can be requested from the authors (questions, protocols, and data).

6. Code availability

All analytic code used to produce this work can be obtained from the corresponding author.

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CRediT authorship contribution statement

Lucien Schneeberger: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Louis Sutter:** Writing – review & editing, Supervision. **Noëlle Valérie Schenk:** Writing – review & editing, Methodology. **Lindsey Norgrove:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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