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Fruit fly management research: A systematic review of monitoring and control tactics in the world

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ABSTRACT

Several fruit fly species are invasive pests that damage quality fruits in horticultural crops and cause significant value losses. The management of fruit flies is challenging due to their biology, adaptation to various regions and wide range of hosts. We assessed the historical and current approaches of fruit fly management research worldwide, and we established the current knowledge of fruit flies by systematically reviewing research on monitoring and control tactics, according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. We performed a systematic review of research outputs from 1952 to 2017, by developing an a priori defined set of criteria for subsequent replication of the review process. This review showed 4900 publications, of which 533 publications matched the criteria. The selected research studies were conducted in 41 countries for 43 fruit fly species of economic importance. Although 46% of the studies were from countries of North America, analysis of the control tactics and studied species showed a wide geographical distribution. Biological control was the most commonly studied control tactic (29%), followed by chemical control (20%), behavioral control, including SIT (18%), and quarantine treatments (17%). Studies on fruit flies continue to be published and provide useful knowledge in the areas of monitoring and control tactics. The limitations and prospects for fruit fly management were analyzed, and we highlight recommendations that will improve future studies.

1. Introduction

Horticultural crops constitute a significant segment of the global agricultural production. The importance of horticulture can be substantiated by its high export value, high yield and returns per unit area (Ravichandra, 2014). Several species of fruit flies (Diptera: Tephritidae) are invasive pests of horticultural crops worldwide, due to their adaptation to various regions, high polyphagia and rapid reproduction (Sarwar, 2015).

Fruit flies cause direct damage to fruits and vegetables by the puncture for oviposition by the female and the larval development inside the fruit (Aluja, 1994). These pests cause direct damage to important export crops leading to losses of 40% up to 80%, depending on locality, variety and season (Kibira et al., 2010). The presence of these pest species limits access to international markets due to quarantine restrictions imposed by importing countries (Lanzavecchia et al., 2014).

Few insects have greater impact on the international marketing of horticultural produce than tephritid fruit flies (Hendrichs, 1996). Countries that harbor these important pests spend millions of dollars each year on control and have trade sanctions imposed by rigorous treatments of products prior to export. Such treatments are effective, but the volume of imported horticultural produce into countries free of these pests raises biosecurity concerns (Dhami et al., 2016). To remain free of fruit flies, New Zealand, for example, spends approximately NZ $1.4 million each year in post-border surveillance alone (Dhami et al., 2016). However, in fruit fly-free countries, such as Chile, this status contributes to the export of up to 50% of fruit production (Retamales and Sepúlveda, 2011).

The management of fruit flies is challenging because third-instar larvae leave decaying fruits and drop to the ground to pupate in the soil; consequently, both larvae and pupae in fruits and soils are protected from surface-applied insecticides (Heve et al., 2016). The control

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of fruit flies is becoming increasingly difficult in many countries, as formerly effective broad-spectrum and systemic-acting insecticides are removed from the market (Böckmann et al., 2014).

Due to progressively more stringent restrictions on the use of insecticides and the increasing demand for healthy food around the world, new environmentally friendly techniques for fruit fly control are arising (Navarro-Llopis et al., 2011). In addition, given the dependence of fruit fly distribution and abundance on climate variables, there are also concerns about the intensification of the climate changes that will facilitate the occurrence of more frequent outbreaks in horticultural regions (Sultana et al., 2017).

In fruit fly management, more than one tactic is frequently required. Each of these tactics has different advantages and disadvantages, and its adoption may or not be available for every case (Suckling et al., 2016). For example, the Male Annihilation Technique (MAT) is applied for some *Bactrocera* species but not for other species, owing to the lack of suitable lures. Additionally, the Sterile Insect Technique (SIT) requires the mass rearing of the target pest and geographic isolation of the release zone (Suckling et al., 2016).

Therefore, it is important to examine the current and historical approaches to fruit fly management research worldwide to enable researchers to evaluate the effectiveness of current research approaches and, if needed, develop more appropriate research protocols. The objective of the present study was to establish the current knowledge on fruit fly management by systematically reviewing research on monitoring and control tactics used for local and regional management of these pests. There is one overarching research question in the present systematic review that can be divided into a series of more focused questions: How has monitoring and control tactics research been conducted worldwide?

- What fruit fly control tactics have been/were studied?
- What methodological approaches were examined?
- What fruit fly species were targeted?
- What localities were studied?
- What are the challenges for fruit fly management?
- What are the prospects for fruit fly management?
- What are the potential knowledge gaps in fruit fly research?

2. Material and methods

2.1. Database sources

We used Web of Science Core Collection, Science Direct, PubMed and Scopus to generate a database of publications that assess fruit fly monitoring and control tactics efforts in a pest management context. The search was limited to these four databases because they contained research articles that were available in full text and had undergone peer-review by scientists. The search was limited to publications written in English, Spanish and Portuguese published in journals from 1952 to 2017.

2.2. Search term

We divided fruit fly monitoring and control tactics into nine categories: 1) monitoring and detection; 2) control with natural product insecticides; 3) bioinsecticides; 4) chemical control; 5) biological control; 6) behavioral control; 7) mechanical control; 8) quarantine; and 9) genetic control. The description of each category is shown in Supplementary information (Supplementary Material 1). We used the following search terms: ("fruit fly" AND "monitoring"), ("fruit fly" AND "natural products"), ("fruit fly" AND "bait"), ("fruit fly" AND "insecticide control"), ("fruit fly" AND "biological control"), ("fruit fly" AND "sterile insect technique"), ("fruit fly" AND "male annihilation technique"), ("fruit fly" AND "mass-trapping"), ("fruit fly" AND "quarantine control"), ("fruit fly" AND "irradiation") and ("fruit fly" AND "RNAi").

2.3. Article screening

The search generated 4900 records (last access date: 13 December 2017), and the results were imported into a library of Mendeley Reference Manager. We removed duplicates, reviews, conference proceedings, editorial material and book chapters. The remaining records were retrieved in full text and inspected in detail. For study inclusion, three criteria were determined: 1) studies with Tephritidae fruit fly species; 2) fruit fly monitoring studies (excluding faunal analysis studies), and 3) studies that used one or more tactics for fruit fly control and assessed effects on biology, physiology and/or behavior (excluding studies of rearing techniques).

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Moher et al., 2009) (PRISMA statement and Checklist) guidelines in including or excluding publications during screening stages. A checklist of the systematic review is shown in Supplementary Material 2.

2.4. Data extraction

For each publication, we collected the full reference and extracted information on the monitoring and control tactics used, the fruit fly species studied, the methodological approach used and the country where the study was performed. Studies that included the species *Bactrocera invadens* (Drew, Tsuruta and White), *Bactrocera papayae* (Drew and Hancock) and *Bactrocera philippinensis* (Drew and Hancock) were added to studies of *Bactrocera dorsalis* (Hendel), the current synonymized species (Hendrichs et al., 2015; Schutze et al., 2015). The methodological approaches used in each study were categorized into laboratory, semifield, field or combined approaches. The combined approach used more than one methodology (e.g., field and laboratory). For studies lacking information on where the research was performed, we used the location of the first author's institution.

2.5. Data analysis

The extracted data were subjected to descriptive analysis (proc UNIVARIATE) and principal component analysis (PCA) (proc PRINCOMP). The PCA was performed to examine any intrinsic variation in the fruit fly studies and whether any clustering was presented. The PCA was performed on the countries (41 variables), species (43 variables), methodological approaches (4 variables) and monitoring and control methods (9 variables) extracted from the studies dataset (Supplementary Material 3). The data for each category were transformed by standardized Euclidean distance analysis prior to PCA, to stabilize the variance of the measured variables and thus give the variables approximately equal weight in the PCA. The statistical analysis was performed using SAS (version 9.0, SAS Institute Inc., Cary, NC, USA) and the results were fitted using Sigma Plot®.

3. Results

A total of 533 publications matched the criteria and were included in the analysis. Full references for all publications and extracted data are presented in Supplementary Material 3. Fig. 1 shows the flow diagram for the systematic review.

3.1. Publication years

A significant increase in the number of published studies has been observed since the 1990s (Fig. 2). However, more than half of the studies were published within the last seven years (n = 290 studies), demonstrating a rapid expansion of fruit fly research since 2010.

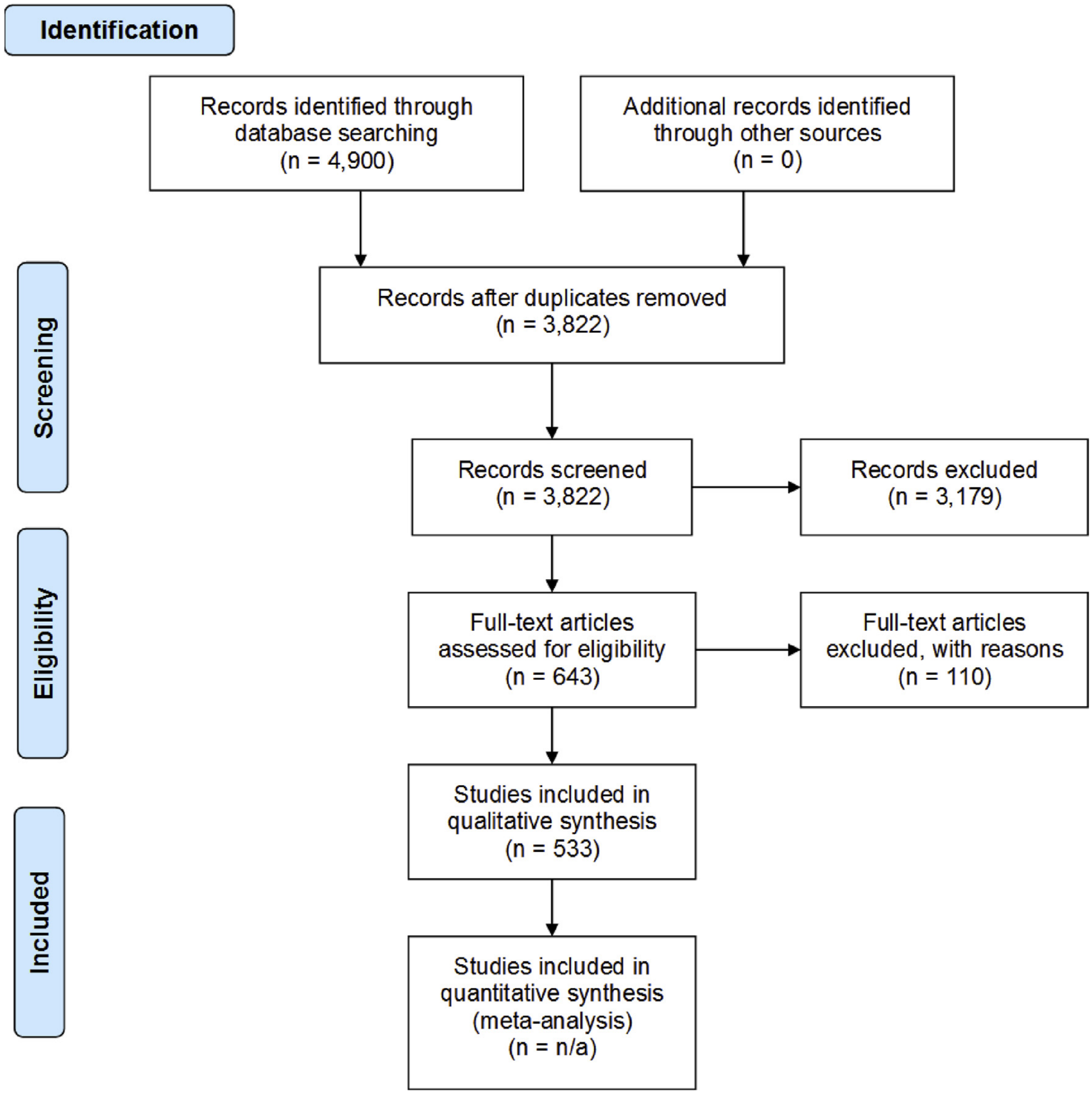

Fig. 1. PRISMA flow diagram. Flow diagram illustrating search strategy.

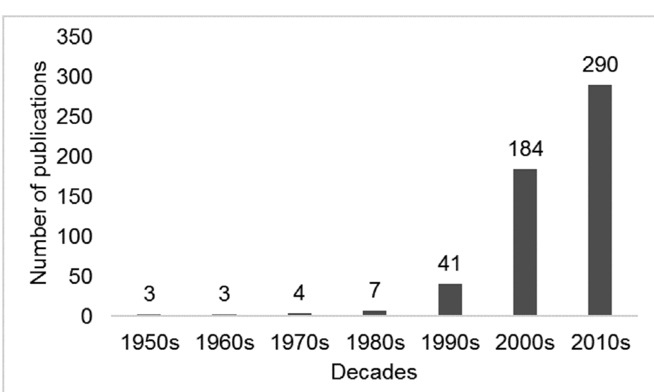

Fig. 2. Temporal trend of fruit fly management research. Studies of monitoring and control tactics of fruit flies from 1952 to 2017 by decade. Last access date 13 December 2017.

3.2. Geographical distribution of studies

Research studies were conducted in 41 countries (Fig. 3). However, 46% of the studies were from countries of North America (n = 248), mainly United States of America (U.S.A.) (n = 173) and Mexico (n = 61). In Europe (n = 93), most of the studies were from Spain (n = 39). Thirteen percent of the studies were from Asia (n = 71), mainly in China (n = 31). Nine percent of the research studies were from South America (n = 47), while seven percent of the studies were from Oceania (n = 40), and six percent of the studies were from Africa (n = 35). In South America, 64% of the studies were from Brazil (n = 31), and in Oceania, 39 studies were from Australia, and one study was from French Polynesia. In Africa, the studies were distributed in eight countries, but most studies were from Kenya and Egypt (n = 9). Publications from the U.S.A. and Spain included monitoring studies and all control tactics searched (Supplementary Material 3). Publications from Central American countries did not meet the present study criteria. The principal control tactics and fruit fly species researched in countries with more than 10 studies found in the present review are shown in Table 1.

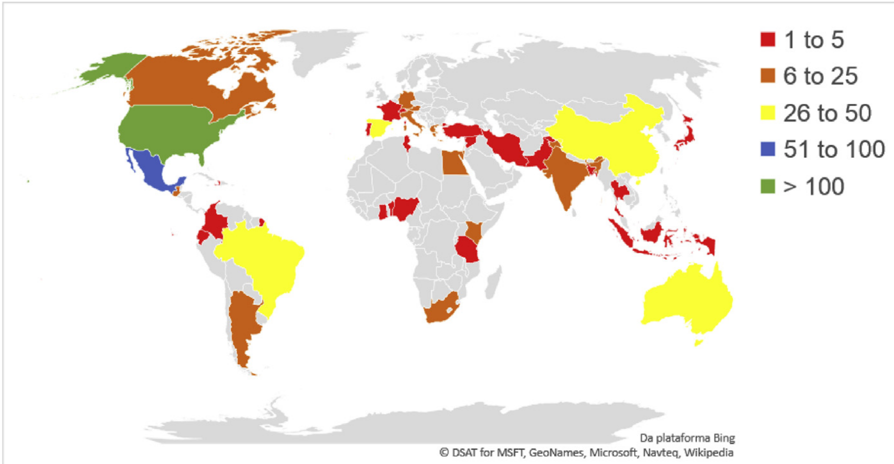

Fig. 3. Geographical distribution of fruit fly management research. Studies of monitoring and control tactics of fruit flies. The number of studies from each country is indicated by category.

Table 1
Principal control tactics and fruit fly species researched in countries with more than 10 studies found in the review.

Country[a]	Principal control tactic	Fruit fly species
USA	Parasitoids and baits [b]	*Ceratitis capitata*
MEX	Biological tactics	*Anastrepha ludens*
AUS	Male Annihilation Technique	*Bactrocera tryoni*
ESP	Other biological agents [c]	*Ceratitis capitata*
BRA	Parasitoids	*Anastrepha fraterculus*
CHN	RNA interference	*Bactrocera dorsalis*
GRC	Mass-trapping	*Bactrocera oleae*
ARG	Parasitoids	*Anastrepha fraterculus*
ITY	Other biological agents [c]	*Ceratitis capitata*
ISR	Several tactics [d]	*Ceratitis capitata*

[a] USA: United States of America; MEX: Mexico; AUS: Australia; ESP: Spain; BRA: Brazil; CHN: China; GRC: Greece; ARG: Argentina; ITY: Italy; ISR: Israel.
[b] Bait spray and station of bioinsecticides and chemical products.
[c] Predators, bacteria, viruses, fungi and nematodes.
[d] Bait spray and station of bioinsecticides and chemical products, pulverization of chemical products, SIT and temperature.

3.3. Fruit fly species

A total of 43 fruit fly species were found in the studies (Table 2). The Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann) was the fruit fly species most studied, with 180 studies, followed by *Anastrepha ludens* (Loew) with 73 studies and *B. dorsalis* with 72 studies. Considering only the fruit fly genus, 37% of the species studied belong to the genus *Ceratitis* or *Bactrocera,* followed by *Anastrepha* (32%), *Rhagoletis* (10%), *Zeugodacus* (8%), *Dacus* (1.1%) and *Toxotrypana* (0.2%).

3.4. Methodological approaches

A total of 343 studies used laboratory approaches, 12 studies used semifield approaches and 241 used field approaches. Fifty-seven studies used combined approaches.

3.5. Monitoring and control tactics

Biological control was the most commonly studied control tactic (29%, n = 154 studies), followed by chemical control (20%, n = 108), behavioral control, including SIT (18%, n = 95), quarantine treatments (17%, n = 89), bioinsecticides (13%, n = 71), control with natural product insecticides (7%, n = 36), mechanical control (6%, n = 31) and genetic control (3%, n = 17). Monitoring was found in 14%

Table 2
Number of studies examining the monitoring and control tactics of fruit fly species.

Fruit fly species	n studies
Ceratitis capitata	180
Anastrepha ludens	73
Bactrocera dorsalis	72
Bactrocera oleae	49
Zeugodacus cucurbitae	40
Bactrocera tryoni	29
Anastrepha fraterculus	28
Anastrepha obliqua	25
Anastrepha suspensa	18
Ragholetis indifferens	18
Ragholetis pomonella	14
Bactrocera zonata	11
Ragholetis cerasi	10
Ragholetis mendax	10
Bactrocera invadens	9
Ceratitis rosa	8
Anastrepha serpentina	7
Ceratitis cosyra	7
Dacus ciliatus	6
Anastrepha spp.[a]	6
Bactrocera carambolae	5
Bactrocera minax	4
Bactrocera papayae	3
Bactrocera spp.[a]	3
Bactrocera tau	3
Zeugodacus cucumis	3
Anastrepha sorurcula	2
Anastrepha leptozona	2
Bactrocera correcta	2
Bactrocera latifrons	2
Anastrepha grandis	1
Anastrepha punensis	1
Anastrepha spatulata	1
Anastrepha distincta	1
Anastrepha chiclayae	1
Anastrepha striata	1
Anastrepha schultzi	1
Anastrepha zenildae	1
Bactrocera jarvisi	1
Bactrocera neohumeralis	1
Bactrocera philippinensis	1
Ceratitis anonae	1
Ceratitis fasciventris	1
Ragholetis cingulata	1
Toxotrypana curvicauda	1

[a] Species not specified in the studies.

Table 3
Studies on monitoring and control tactics of fruit flies and principal fruit fly species researched in each tactic.

Monitoring and control tactics		n studies	Fruit fly species
Monitoring and detection	Fruits	2	*Anastrepha* and *Rhagoletis* species [a]
	Traps	59	*Ceratitis capitata*
	PCR	7	*Bactorcera dorsalis* and *Bactrocera oleae*
	Automatic	7	*Bactrocera dorsalis*
Natural products	Bait spray and bait station	8	*Ceratitis capitata*
	Pulverization	21	*Ceratitis capitata*
	Biofilm, feeding and injection	7	*Zeugodacus cucurbitae*
Bioinsecticides	Bait spray and bait station	50	*Ceratitis capitata*
	Pulverization	20	*Ceratitis capitata*
	Feeding	1	*Bactrocera dorsalis* and *Zeugodacus cucurbitae*
Chemical	Bait spray and bait station	68	*Ceratitis capitata*
	Pulverization	40	*Ceratitis capitata*
Biological	Parasitoids	84	*Ceratitis capitata*
	Predators, bacteria, viruses, fungi and nematodes	70	*Ceratitis capitata*
Behavior	Sterile Insect Technique	52	*Ceratitis capitata*
	Male Annihilation Technique	43	*Bactrocera dorsalis*
Mechanical	Mass-trapping	26	*Bactrocera oleae* and *Ceratitis capitata*
	Fruit bagging and clipping infested fruits	5	*Anastrepha fraterculus*, *Ceratitis capitata* and *Zeugodacus cucurbitae*
Quarantine	Modified atmosphere	8	*Anastrepha ludens*
	Temperature	30	*Ceratitis capitata*
	Irradiation	48	*Anastrepha ludens* and *Ceratitis capitata*
	Metabolic stress	1	*Bactrocera dorsalis, Ceratitis capitata* and *Zeugodacus cucurbitae*
	Microwave	1	*Anastrepha ludens*
	Pulsed electric field	1	*Anastrepha ludens*
Genetic	RNA interference	17	*Bactrocera dorsalis*

[a] *Anastrepha fraterculus, Anastrepha ludens Anastrepha obliqua Anastrepha leptozona Anastrepha distincta Anastrepha chiclayae Anastrepha striata, Rhagoletis indifferens* and *Rhagoletis pomonella*.

(n = 75) of studies (Table 3).

3.6. Statistical analysis

The PCA separated the methodological approaches into three groups. The first two principal components explained 97.40% (PCI = 82.16% and PCII = 15.24%) of the total variance (Fig. 4). For monitoring and control methods, the first two principal components explained 81.54% (PCI = 69.73% and PCII = 11.84%) of the total variance, and the PCA showed four groups for this category (Fig. 5). The association tendency for these findings is shown in the Discussion. For countries and species, the PCA did not showed a separation among the categories.

4. Discussion

4.1. Publication years

The first fruit fly study found in the present systematic review was published in 1952 (Steiner, 1952) and refers to the use of bait spray for

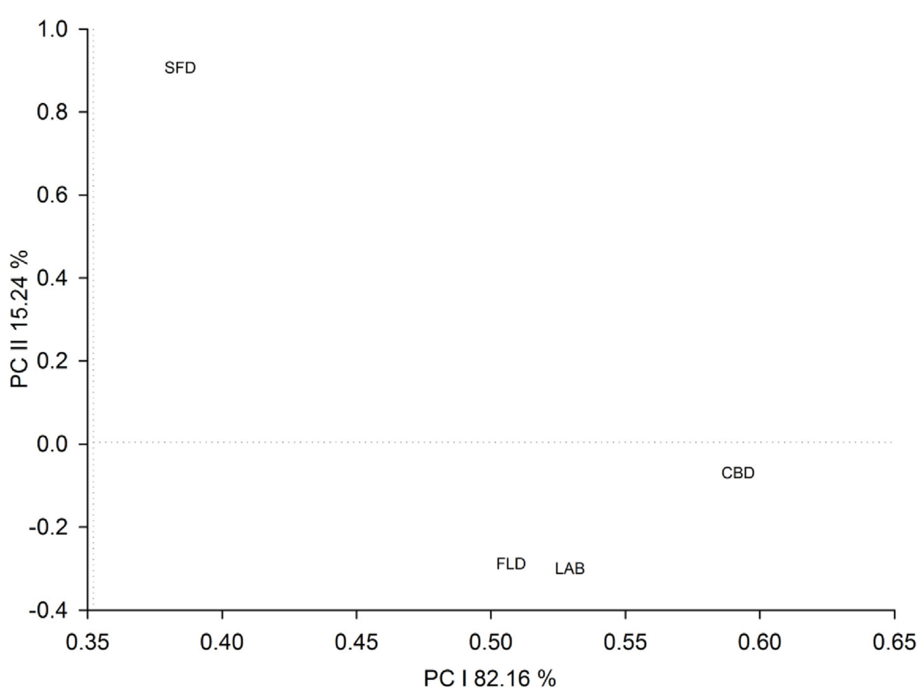

Fig. 4. Principal component analysis of methodological approaches used in fruit fly studies. CBD: combined approaches; FLD: field; LAB: laboratory and SFD: semifield.

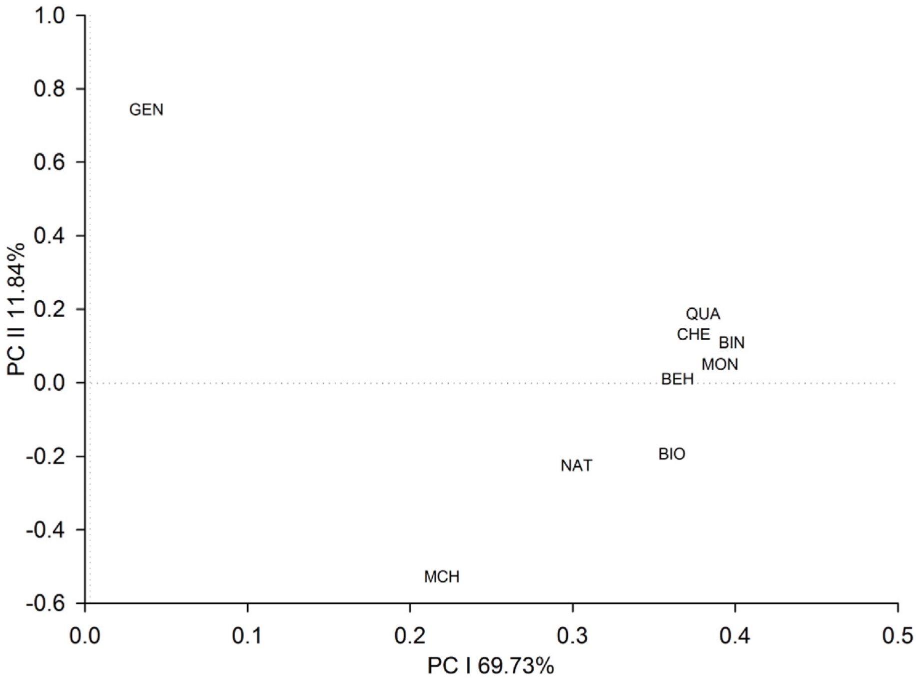

Fig. 5. Principal component analysis for control methods used in fruit fly studies. BEH: behavioral control; BIO: biological control; BIN: bioinsecticides; CHE: chemical control; GEN: genetic control; MCH: mechanical control; MON: monitoring and detection; NAT: control with natural product insecticides and QUA: quarantine treatments.

control of *B. dorsalis* in Hawaii. Subsequently, the number of publications remained low until the late 1980s. The construction of mass rearing of sterile insects and parasitoids seems to have stimulated fruit fly research in the 1990s. The first fruit fly production and sterilization facility (MOSCAMED) was installed in Mexico (Metapa de Domínguez, Chiapas) in 1979, shortly after the introduction of *C. capitata* in Guatemala and Mexico in 1976 and 1977, respectively (Enkerlin et al., 2017). In 1992, Mexico initiated a national fruit fly control program against native *Anastrepha* species, based on the application of selective toxic baits, the use of the SIT and the augmentative releases of parasitoids to develop fruit fly-free areas (Enkerlin et al., 2017; Montoya et al., 2007). For this purpose, the MOSCAFRUT mass rearing center was built in Metapa de Domínguez to produce sterile flies of two *Anastrepha* species [*A. ludens* and *Anastrepha obliqua* (Macquart)] and the endoparasitoid *Diachasmimorpha longicaudata* (Ashmead) (Hymenoptera: Braconidae) (Enkerlin et al., 2017). Additionally, other countries, such as Guatemala (Enkerlin et al., 2017), Argentina (Longo et al., 2000) and Chile (Enkerlin et al., 2003) also established fruit fly centers.

Numbers of publications started to increase substantially in the 1990s, which also coincides with the first eradication attempts of invasive fruit fly species. Because of the control programs established in the 1980s and 1990s, the eradication of important species, such as *C. capitata* in southern Mexico (1982) (Hendrichs et al., 1983) and northern Chile (1995) (Olalquiaga and Lobos, 1993) and *Zeugodacus* (Zeugodacus) *cucurbitae* (Coquillett) (formerly *Bactrocera* (Zeugodacus) *cucurbitae*) in southern Japan (1993) (Kuba et al., 1996), was achieved through SIT and bait spray (Suckling et al., 2016).

4.2. Geographical distribution of studies

Studies performed in Argentina, Brazil, and Kenya were mainly related to biological control with parasitoids. In South America, most studies were conducted in Brazil using the parasitoid *D. longicaudata*. This parasitoid was introduced in Brazil in 1994, and the studies found in the present review are related to parasitism capacity (Alvarenga et al., 2005; Meirelles et al., 2016), dispersion patterns (Paranhos et al., 2007), competition with native parasitoids (Paranhos et al., 2013) and interaction with other control tactics (Alvarenga et al., 2012).

Fruit fly research with bait spray was performed in the U.S.A, Israel, and Mexico, the latter having conducted the same number of studies with bait spray as with biological control tactics. Italy, Spain, and Egypt also used biological tactics (except parasitoids) in research. Research with natural product insecticides was performed in India, and the mass-trapping tactic was performed in Greece. Australia had the most publications related to male annihilation technique (MAT).

Recent technological advances in fruit fly control research were reported in China (Ali et al., 2017; Chen et al., 2008, 2011; Shen et al., 2013; Peng et al., 2015; Suganya et al., 2010, 2011; Zheng et al., 2012; Xiong et al., 2016). These studies examined the use of RNA interference in species native to the Asian continent, such as *B. dorsalis*.

4.3. Fruit fly species

Most studies of fruit fly control included the Mediterranean fruit fly *C. capitata.* Its high polyphagia and ability to adapt to wide-ranging climate conditions better than most other species of tropical fruit flies contribute its rank of first among economically important fruit fly species (Liquido et al., 1990). The Mediterranean fruit fly infests over 300 species of cultivated and wild fruits, vegetables and nuts, the widest known host range of any pest fruit fly (Leftwich et al., 2014). Although endemic to Africa, this species is currently present on all continents (Szyniszewska and Tatem, 2014). This species was included in the main control tactics found in the present review (Table 3).

The species *B. dorsalis* and *A. ludens* were among the species with the highest number of publications. Native to Asia, *B. dorsalis* was included in studies performed in 14 countries, and research focused on various tactics; only mechanical control was not found in this review. *B. dorsalis* was the main species researched in MAT and RNAi studies (Table 3). Studies of *A. ludens* were concentrated in Mexico and U.S.A. *Anastrepha ludens*, together with *C. capitata*, were the main species included in studies of quarantine treatments using irradiation.

The melon fruit fly, *Z. cucurbitae*, was highlighted among the most studied species of the Tephritidae family. This species was included in 67% of the control tactics analyzed. *Zeogodacus cucurbitae* is a widely distributed and harmful pest, mainly affecting cucurbitaceous crops (Shishir et al., 2015). The damage caused by the larvae feeding on the fruit can reach 90% of the crop yield (Ryckewaert et al., 2010).

4.4. Methodological approaches

Laboratory studies were more common, followed by field studies, performed in 33 and 36 countries, respectively. Studies that included semifield assays were performed in six countries. Additionally, 10% of the studies used more than one approach. In the PCA, laboratory and field approaches showed separation of the semifield and combined approaches (Fig. 4).

The fruit fly management studies found in the present review that were conducted in the laboratory were important to determine the essential aspects of control tactics, and included studies on doses and efficacy of phytosanitary treatments (Sharp and Polavarapu, 1999; Hallman and Thomas, 2010), effects on the biological parameters (Juan-Blasco et al., 2013; Rempoulakis et al., 2015), selection of attractants for traps (Katsoyannos et al., 2000), performance and potential of biological control agents (Bokonon-Ganta et al., 2005). However, field studies were critical to evaluate the response of fruit flies to control tactics under uncontrolled conditions (Aluja et al., 2009; Ali et al., 2016).

4.5. Fruit fly monitoring

Prevention is one of the most effective strategies for fruit fly management (Aluja, 1999). The monitoring of fruit flies is crucial to determine the population dynamics, compare infestation levels between different sites and evaluate the effectiveness of a control tactic (Eliopoulos, 2007; Enkerlin et al., 1996). However, only 14% of the studies presented results for monitoring fruit flies (14%). Most monitoring studies were performed in Mexico and could be assigned to a single category, monitoring with traps (Lasa et al., 2014; Malo et al., 2012). These studies were mainly conducted in *C. capitata* (Table 3).

The present review also found studies using polymerase chain reaction (PCR) for detecting the DNA of fruit flies and biological control agents (Dhami et al., 2016; Mathé-Hubert et al., 2013; Rejili et al., 2016), and this tool has been widely used for various pest groups. PCR-based assays provide a highly sensitive, rapid and accurate technique to detect pests in various biosecurity and ecological applications (Dhami et al., 2016). This tool was used for five fruit fly species.

The correct identification of insects is a basic premise for pest management. However, the identification of fruit flies is manually performed by few specialists through morphological analysis. Brazilian researchers implemented a classifier multimodal fusion approach, using two types of images (wings and aculei), generating promising results for the identification of *Anastrepha* species. The results showed more than 98% classification accuracy, which is remarkable, despite the technical problems (Faria et al., 2014).

The risk of not detecting early or not responding immediately to the detections of exotic fruit flies can be illustrated by cases where eradication failed, such as *B. carambolae* in Suriname. This example illustrates the lag phase from initial detection in infested fruits in 1975 to species identification in 1986 and confirmation that the specimen had come from South-east Asia four years later (Suckling et al., 2016). Forecasting models of pests, such as CLIMEX (Sridhar et al., 2017), and VARMAX (Chuang et al., 2014), can enable the monitoring of fruit flies to make preemptive and effective pest management decisions prior to the occurrence of real problems (Chuang et al., 2014).

Fruit fly monitoring with traps is currently performed with manual weekly counting. However, this method is costly and time-consuming, resulting in a suboptimal spraying frequency (overdue or unnecessary spraying) (Goldshtein et al., 2017). Recently, an online method was proposed for the detection of infested fruits in orchards. An algorithm has been developed to identify spots generated in hyperspectral images of mangoes infested with fruit fly larvae. The algorithm incorporates background removal, application of a Gaussian blur, thresholding, and particle count analysis to identify the locations of infestations. This study demonstrates the feasibility of hyperspectral imaging for fruit fly detection while highlighting the need for technology with improved resolution and signal to noise ratio to enable the detection of single larvae (Haff et al., 2013).

In this context, efforts to develop automatic insect traps have been intensified and accelerated. A recent study showed the first automatic trap for *C. capitata* monitoring, with optical sensors for detecting and counting dead or stunted flies (Goldshtein et al., 2017). The automatic and conventional traps had similar trapping efficiencies under field conditions. The accuracy of the automatic trap counts ranged between 88% and 100% and the overestimate rate was three flies, mostly due to ants and rain. However, the authors emphasized that any change in trap shape and components may have adverse effects on pheromone release or the attractiveness of traps to the insect, which in turn alters the efficiency of the traps (Epsky et al., 1999; Kehat et al., 1994). Moreover, unlike imaging systems, in automatic traps, the insects are not identified; therefore, the lure must be specific to the target pest to avoid erroneous counts caused by non-target species.

4.6. Fruit fly control tactics

Although various control tactics are available for fruit fly management, the present results demonstrate that most of the published studies focused on biological control, followed by chemical, behavioral control (including SIT) and quarantine treatments.

4.6.1. Biological control

Studies of biological control were performed for 29 fruit fly species in 26 countries, highlighting the use of parasitoids (Supplementary Material 3). Parasitoids of the Braconidae family were the main natural enemies of fruit flies studied and included *D. longicaudata* and *Psyttalia* spp. [*Psyttalia concolor, Psyttalia fletcheri, Psyttalia lounsburyi, Psyttalia ponerophaga* and *Psyttalia humilis* (Silvestri)] (Bon et al., 2016; Miranda et al., 2008; Mohamed et al., 2008; Montoya et al., 2016; Ovruski et al., 2007; Ovruski and Schliserman, 2012). The egg parasitoid, *Fopius arisanus* (Sonan) (Hymenoptera: Braconidae), and the pupal parasitoids *Coptera haywardi* Loiácono (Hymenoptera: Diapriidae) and *Aganaspis daci* (Weld) (Hymenoptera: Figitidae) are considered as alternative species to fruit fly biological control with larval parasitoids (Ali et al., 2014, 2016; Appiah et al., 2014; Cancino et al., 2014; Guillén et al., 2002; Zamek et al., 2012).

Research in Latin America has included biological control with native parasitoids of the Neotropical region. These studies mainly include assays of interspecific competition, such as the species *Doryctobracon areolatus* (Szepligeti), *D. crawfordi* (Viereck) and *Utetes anastrephae* (Viereck) (Aluja et al., 2013; Miranda et al., 2015; Paranhos et al., 2013). Some studies included the evaluation of the efficacy of augmentative releases of parasitoids using *D. longicaudata* and *D. tryony* (Cameron).

The control with entomopathogenic fungi has shown interesting results. For *Rhagoletis cerasi* (L.), the control with *Beauveria bassiana* (Balsamo) Vuillemin, *Isaria fumosorosea* (Wize) and *Metarhizium anisopliae* Sorokin caused 90–100% mortality and had the strongest influence on fecundity in laboratory (Daniel and Wyss, 2009). In field tests, the infestation of this species in cherry trees was reduced by 65% using foliar applications of *Beauveria bassiana* (Daniel and Wyss, 2010). Promising results were obtained for the control of *C. capitata* (Castillo et al., 2000; Toledo et al., 2017; Yousef et al., 2014), *Bactrocera oleae* (Gmelin) (Yousef et al., 2013) and *Z. cucurbitae* (Sookar et al., 2014) using entomophatogenic fungi species.

Recently, the pathogenicity of three formulations of *B. bassiana* and their applications in autoinoculation devices and by means of sterile males as vectors, was tested for the control of *C. capitata* in coffee-producing areas of Guatemala (Toledo et al., 2017). The release of sterile male vectors was more effective than the autoinoculation devices in terms of transmitting the conidia to the wild population, but the total population reduction was over 90% for both treatments. The median survival time between the sterile male vectors and the autoinoculation devices was similar, which is considered suitable for strategies, as this enables the vector to live for enough time to disseminate the inoculum among wild individuals (Toledo et al., 2007; Flores et al., 2013). Higher virulence would reduce the chances for horizontal transmission for the control of pest populations in specific patches or hot spots where additional control tactic is required. However, the inoculation of sterile males is still controversial because of its possible effects on quality control parameters and higher cost of this approach, giving rise to a new proposal of integrating the SIT with the use of autoinoculation devices, where a synergistic effect may occur (Montoya, Personal communication).

Entomopathogenic nematodes, such as *Heterorhabditis* spp. (Rhabditida: Heterorhabditidae) and *Steinernema* spp. (Rhabditida: Steinernematidae), were used for control of larvae and pupae of various fruit fly species. The present review found studies with *A. fraterculus* (Barbosa-Negrisoli et al., 2009; Foelkel et al., 2017), *A. ludens* (Lezama-Gutiérrez et al., 2006), *A. suspensa* (Heve et al., 2016), *B. oleae* (Torrini et al., 2017), *B. tryoni* (Langford et al., 2014), *C. capitata* (Malan and Manrakhan, 2009), *Ceratitis rosa* Karsh (Malan and Manrakhan, 2009), *Dacus ciliatus* Loew (Kamali et al., 2013) and *R. cerasi* (Kepenecki et al., 2015). The results were variable for each fruit fly species, with mortalities between 14 and 96%. Some studies suggest that soil type is a critical factor that should be considered when selecting the nematode species and planning fruit fly biological control strategies (Lezama-Gutiérrez et al., 2006).

4.6.2. Chemical control

Chemical control studies included the use of baits (spray or station) and insecticide pulverization. The bait spray consists of an attractant mixed with an insecticide (Roessler, 1989). Bait stations are defined as discrete containers of attractants and toxins that attract the pest to the insecticide (Heath et al., 2009). In this case, the toxin can kill, sterilize or infect the target insect (Navarro-Llopis et al., 2010). The application of bait sprays with insecticide should be considered a lure-and-kill method but using higher amounts of insecticide (Navarro-Llopis et al., 2012).

Chemical control was used against 21 fruit fly species in 20 countries. The bait spray and station were the main tactics included in all chemical control studies, except in Spain, that included mainly the insecticide pulverization tactic (Supplementary Material 3). The efficacy of insecticides (such as imidacloprid, chlorpyrifos, thiacloprid, malathion, zeta-cypermethrin and fipronil) was also studied with *A. fraterculus*, *A. ludens*, *A. suspensa*, *Z. cucurbitae*, *B. dorsalis*, *C. capitata* and *Rhagoletis indifferens* Curran (Conway and Forrester, 2011; Harter et al., 2015; Juan-Blasco et al., 2013; Liburd et al., 2004; Yee and Alston, 2006, 2012).

In a recent study, bait spray was used in a perimeter control approach in non-crop vegetation for the management of *Zeugodacus cucumis* (French) in Australia. Control in *Z. cucumis* in vegetable crops presents different challenges, since flies use these crops only for oviposition, spending most of their time in shelters outside the growing area (Senior et al., 2015). Thus, the application of bait spray to plants used as shelter is an important tool for the control of fruit flies (Senior et al., 2015). A similar study was performed for *B. tryoni* and *Z. cucumis* through the application of bait in eight plant species and applied at three heights. When protein bait was applied at different heights, *B. tryoni* primarily responded to bait placed in the upper part of the plants, whereas *Z. cucumis* preferred bait placed lower on the plants. These results have implications for the optimal placement of protein bait for control of fruit flies in vegetable crops and suggest that the two species exhibit different foraging behaviors (Senior et al., 2017).

Insecticide resistance studies with fruit flies have focused mainly on the following species: *C. capitata* (Arouri et al., 2015; Magaña et al., 2007), *B. oleae* (Kakani et al., 2010), *B. dorsalis* (Zhang et al., 2014) and *Z. cucurbitae* (Hsu et al., 2015). Knowledge of the underlying molecular mechanisms associated with insecticide resistance is relatively limited in Tephritidae species (Vontas et al., 2011). This limitation may be due to shortage of genome and transcriptome data, currently described for few species, as *B. dorsalis* (Shen et al., 2011), *B. oleae* (Pavlidi et al., 2013, 2017), *C. capitata* (Gomulski et al., 2012; Salvemini et al., 2014), *Z. cucurbitae* (Sim et al., 2015) and *Bactrocera minax* (Enderlein) (Dong et al., 2014).

The rate of insecticide resistance development may vary among Tephritid fruit fly species for several reasons, including genetic/biological differences (number of generations, life cycle, fecundity, polygamy, migration and dispersal rates) and operational factors (selection pressure – type of applications: bait vs. cover sprays, role of refugia) in different ecological situations (Vontas et al., 2011). For example, spinosad sprays have led to resistance development in *B. oleae* after 10 years of use in California (Kakani et al., 2010), likely due to the limited selection pressure imposed by the bioinsecticide bait applications. However, resistance has now evolved and is becoming a problem to chemical products, such as the case of *C. capitata* in Spain where malathion and lambda-cyhalothrin resistance levels have led to field failures (Arouri et al., 2015; Magaña et al., 2007).

4.6.3. Behavioral control

The behavioral control studies included two main tactics, SIT and MAT. These studies included 20 fruit fly species in 24 countries. Studies of SIT included 12 fruit fly species, mainly *C. capitata, A. ludens* and *B. dorsalis* (Supplementary Material 3). The geographical distribution of these studies was mainly concentrated in Latin America, U.S.A. and Australia. For *Rhagoletis* species, only *R. mendax* was included in SIT studies. Many studies that included SIT evaluated basic factors of sterile insects, such as mating competitiveness, capacity of dispersion, survival, fertility, and basic parameters for application techniques (irradiation doses and efficacy) (Barry et al., 2004; Dominiak et al., 2014; McInnis and Wong, 1990; McInnis et al., 2002; Rempoulakis et al., 2015).

In its application, SIT still faces challenges, such as the determination of sterile fly release densities required to achieve effective sterile to wild ratios for the suppression or eradication of wild populations (Aluja, 1994). This aspect was recently evaluated in *A. ludens* (Flores et al., 2014) and *A. obliqua* (Flores et al., 2017) in mango orchards. The decline of sterility in fertile females was evaluated using different ratios of sterile: fertile males under field cage conditions. The trajectory of sterility slowed down after a sterile: wild ratio of 30:1 in *A. ludens*. A 10:1 sterile: wild ratio induced approximately 80% sterility in *A. obliqua* cohorts. For *C. capitata*, a strong negative relationship between the proportion of sperm and offspring was established by Juan-Blasco et al. (2014). In this study, the proportion of V8 sperm in spermathecae increased with temperature and with the number of V8 males released but leveled off between ratios of wild females to wild males to V8 males of 1:1:10 and 1:1:20. In all seasons, except winter (no offspring), viable offspring increased with temperature and was lowest for ratio 1:1:20.

Some studies have evaluated the performance of parasitoids reared in a sterile fruit fly, such as *P. concolor* reared on larvae of *C. capitata* (Hepdurgun et al., 2009), *P. humillis* reared in *B. oleae* (Yokoyama et al., 2012) and *D. longicaudata* reared in *C. capitata* (Viscarret et al., 2012) and *A. fraterculus* (Costa et al., 2016). Other studies included the evaluation of anti-predator behavior of irradiated larvae of *A. ludens* (González-López et al., 2015; Ponce et al., 1993; Rao et al., 2014), the production of pheromones in irradiated males of *A. suspensa*, and the structure of the intestinal microbiota of *C. capitata* (Ami et al., 2009). The inhibition of protein expression in irradiated pupae of *B. dorsalis* was recently described (Chang et al., 2015).

Studies of MAT were performed in 17 countries for 16 fruit fly species. *B. dorsalis* was the main species included in MAT studies (Table 3). These studies evaluated the use of attractants and insecticides for male capture (Ndlela et al., 2016; Reynolds et al., 2016; Vargas et al., 2012, 2015). The impact of methyl eugenol and malathion, used for MAT was evaluated on non-target insects during the eradication program for *Bactrocera carambolae* Drew and Hancock (Vayssières et al., 2007). The results demonstrated that the use of blocks impregnated with methyl eugenol and malathion had no more impact on non-target insects than a non-impregnated block.

Studies aiming to integrate MAT with other techniques, such as SIT, bait spray, parasitoids and the removal of infested fruits, were found in the present review (Barclay et al., 2014; Shelly and Villalobos, 1995; Vargas et al., 2010). This may be a function of scale, as MAT is sufficient for small populations, while bait sprays, for example, are included to kill reproducing females in hot spots of larger populations (Suckling et al., 2016). Additionally, the MAT involves minimal cost and labor as it does not require frequent application (Lloyd et al., 2010).

4.6.4. Quarantine treatments

Studies that included quarantine treatments were performed for 23 species in 14 countries (Supplementary Material 3). Irradiation was the tactic most used for 20 species, mainly *C. capitata* and *A. ludens* (Table 3). Factors for fruit irradiation control efficacy, such as radiation doses, were determined for various fruit fly species, including *A. fraterculus* (Allinghi et al., 2007), *A. ludens* (Hallman and Worley, 1999), *A. obliqua* (Hallman and Worley, 1999), *B. latifrons* (Follett et al., 2011), *B. tryoni* (Collins et al., 2009), *B. zonata* (Draz et al., 2016), *C. capitata* (Mansour and Franz, 1996), *D. ciliates* (Rempoulakis et al., 2015) and *R. mendax* (Sharp and Polavarapu, 1999).

The temperature was the second quarantine treatment researched for 12 species, mainly *C. capitata* (Table 3). In *Anastrepha grandis* (Macquart), temperature treatment was applied to determine the development stage more tolerant to cold in zucchini squash [*Cucurbita pepo* L. (Cucurbitaceae)]. The authors found that the 3rd instar was the most tolerant stage, and the time required for a cold treatment in zucchini squash when treated at a minimum of 1.0 °C was estimated at ~23 d (Hallman et al., 2017). However, the estimated time of 23 d needs to be confirmed by large-scale testing before it should be used commercially.

4.6.5. Bioinsecticides

Studies that included bioinsecticides were performed in 17 countries for 18 fruit fly species, mainly *C. capitata*, *R. indifferens* and *A. ludens* (Supplementary Material 3). These studies included formulated bio-based products, e.g spinosad-based (GF-120™); a fermentation by-product of the bacteria *Saccharopolyspora spinosa* Mertz & Yao (Thompson et al., 2000) and plant-derived, e.g. neem (Nimbicidine®).

The main studies related to control with bioinsecticides evaluated the use of spinosad-based baits. These studies evaluated factors such as residual control and lethal concentrations (Flores et al., 2011), attractiveness and efficacy of baits (Mangan et al., 2006; Prokopy et al., 2003; Yee et al., 2007), toxicity to fruit flies (Michaud, 2003) and effects on foraging and biological parameters of fruit fly species (Barry et al., 2003; González-Cobos et al., 2016). The main biological parameters evaluated were emergence, mortality, and oviposition (Barry and Polavarapu, 2005; Yee and Chapman, 2005; Yee and Alston, 2006; Yee, 2011).

Some studies have evaluated the toxicity of baits and insecticides to beneficial insects, such as parasitoids of tephritids *F. arisanus*, *P. fletcheri, Diachasmimorpha tryoni* (Cameron) and *D. longicaudata* (Liburd et al., 2004; Stark et al., 2004; Urbaneja et al., 2009; Wang et al., 2005) and other natural enemies (Michaud, 2003). These studies confirmed that adult *F. arisanus*, the major parasitoid of *C. capitata* in Hawaii (as a model species), do not feed directly on GF-120™ in either the presence or the absence of honey and water resources in the laboratory (Wang et al., 2005). Other natural enemies also showed similar results (Michaud, 2003).

Studies with *Apis mellifera* L. (Hymenoptera, Apidae) demonstrated that the bait GF-120™ was toxic to honey bees at varying levels, depending on exposure and drying time (Edwards et al., 2003). In another study, Gómez-Escobar et al. (2014) showed that GF-120™ repels *Trigona fulviventris* (Guérin) and *Scaptotrigona mexicana* (Guérin-Meneville). This same study, the repellency was not as marked for *A. mellifera*, when GF-120™ was combined with highly nutritious substances, such as honey. These results suggest that area-wide application of GF-120™ should be carefully monitored, mainly in situations where the release or conservation of parasitoids and other beneficial insects are a prime concern (Wang et al., 2005).

4.6.6. Control with natural product insecticides

Natural product insecticides were used for control of 12 fruit fly species in 16 countries (Supplementary Material 3). These studies included mainly plant and fungi extracts.

Plant-derived insecticides, such as azadirachtins, were included in these studies (Singh, 2003; Silva et al., 2013). The interaction of neem used for *C. capitata* control and the use of parasitoids *D. longicaudata* was also evaluated. Both the botanical insecticide and the parasitism caused larval/pupal mortality and reduced the emergence of *C. capitata* flies. However, the neem negatively affected parasitoid emergence and the effect of parasitism coupled to neem did not provide greater reduction in *C. capitata* emergence than when parasitism was used alone (Alvarenga et al., 2012). The PCA showed that the control with natural product insecticides and biological control were included in the same group (Fig. 5).

4.6.7. Mechanical control

The mechanical control studies included mass-trapping, fruit bagging, and clipping of infested fruits. This method was researched in 11 countries for eight species, mainly *C. capitata* and *B. oleae*. Mass trapping was the main tactic included in these studies. This tactic has the potential to minimize or avoid the use of insecticides and has attracted interest due to their efficacy, specificity and low environmental impact (Navarro-Llopis et al., 2008). Mass trapping consists of the use of traps and baits that release specific volatile substances that attract insects to the trap, in which fruit flies are captured and killed (El-Sayed et al., 2009). However, for some fruit fly species, the use of mass trapping as a control tool depends on the availability of an effective and cheap attractant (Villalobos et al., 2017). Additionally, this technique is most applicable where the cost of labor is low as it is labor intensive. In the PCA, mechanical control showed separation from other methods, likely because this technique was found for a few species in this review (Fig. 5).

4.6.8. Genetic control

Genetic control involved the use of RNA interference (RNAi), which is a mechanism of gene regulation and an antiviral defense system in cells, resulting in the sequence-specific degradation of mRNAs (Huvenne and Smagghe, 2010; Palli, 2012). The present review found studies of RNAi with *B. dorsalis* (Chen et al., 2008), *B. minax* (Xiong et al., 2016), *A. suspensa* (Schetelig et al., 2012) and *C. capitata* (Gabrieli et al., 2016). In these studies, the silencing and expression of genes, such as *transformer* (tra), *trehalose-6-phosphate synthase* (TPS), *yolk protein* (YP), *doublesex* (dsx), and *odorant receptor co-receptor* (Orco), among others, were evaluated. The effects of genetic control on biological parameters, sex determination and behavior were evaluated. These studies were performed in four countries, with 82% of the studies performed in China in *B. dorsalis* (Supplementary Material 3). As with mechanical control, the PCA showed separation of genetic control from the other methods (Fig. 5).

4.7. Limitations and prospects

Fruit fly monitoring was included in some studies, with Mexico being the country that performed most of such studies, mainly using traps. Studies of monitoring with automatic traps showed potential to improve the effectiveness and efficiency of monitoring (Goldshtein et al., 2017). These traps reduce human involvement using cameras and communication technology and may reduce costs in locations with high labor costs (Suckling et al., 2016), but this alternative is still not commercially available. The mapping of population fluctuation, using tools such as geographic information systems, was highly recommended for fruit fly management (Nestel et al., 1997). However, these tools require adjustments for specific field configurations and conditions and are dependent on the development of specific attractants for fruit fly detection.

The present systematic review found many studies that included the use of biological, chemical and behavioral control. Studies with entomopathogenic fungi species showed promising results for biological control of fruit flies. The entomopathogenic fungi, *M. anisopliae*, was used to investigate horizontal transmission capacity among fruit fly adults during mating. The results showed the capacity of transmission from treated flies to non-treated flies, resulting in high mortality and the reduction of the number of eggs produced by fruit fly females (Quesada-Moraga et al., 2008; Sookar et al., 2014). The results of pathogenicity indicate that entomopathogenic fungi could be utilized with different modes of application, such as cover or bait spray (Beris et al., 2013) or infection traps (Navarro-Llopis et al., 2015).

Although many studies have included the use of attractants, such as bait stations, mass trapping, and MAT, studies that include specific attractants remain scarce. It is a problem particularly for the *Anastrepha* species, where there is not a dry trap for monitoring these species. Inclusion in the surveillance networks of food-based lures that capture both females and males is useful. However, food-based lures often lack species specificity, although their deployment is essential to detect species (Suckling et al., 2016).

Although many studies have included the use of attractants for application in tactics, such as bait stations, mass trapping, and MAT, studies that include specific attractants remain scarce. Male fruit flies are usually attracted by parapheromones (IAEA, 2003). In contrast, lures for attracting female fruit flies into traps are based primarily on food or host lures (Dominiak and Nicol, 2010). Inclusion in monitoring networks of food-based lures that capture both females and males is useful. However, although their deployment is essential to detect species, food-based lures often lack specificity (Suckling et al., 2016). For *B. tryoni*, wet-food-based McPhail traps collected more males than females despite their reputation as being a specialist female lure (Dominiak and Nicol, 2010). It is a problem particularly for the *Anastrepha* species, where a dry trap for these species is not available.

Among recent technologies, RNAi is a promising tactic to control target species (Andrade and Hunter, 2017). The RNAi effectiveness varies depending on the species and target gene. Therefore, success in pest control mediated by RNAi requires validation for each species and stage of development prior to its use as a pest control tool (Taning et al., 2016). Similarly, it is essential to identify an appropriate delivery method for the cropping system and pest. For most horticultural crops, topically applied RNAi (e.g., Spray Induced Gene Silencing) (Wang and Jin, 2017), could be an interesting alternative for use by growers (Andrade and Hunter, 2017). To this end, the stability and uptake of the dsRNA in the field must be improved (e.g., nanoparticles, such as nanosheets) (Mitter et al., 2017), and the factors governing the systemic movement of dsRNA within the plant need to be understood (Wang and Jin, 2017). The increase in the number of the fruit fly transcriptome studies has contributed to the progress of RNAi-based assays. Thus, progress in the identification of target gene studies for fruit flies will stimulate the advancement in the generation of application technology for the control of fruit flies.

5. Conclusions

Studies on fruit flies continue to increase and provide useful knowledge to those working in the areas of monitoring and control tactics. From the 1950s to the present day, there has been an emphasis on chemical control research, especially the use of baits (Conway and Forrester, 2011; Díaz-Fleischer et al., 2017; Steiner, 1952). However, the continued use of insecticides is increasingly limited, making it necessary to evaluate other control strategies for inclusion in fruit fly management.

Many advances in biological control tactics, SIT, quarantine treatments and next-generation tools have been described (Ali et al., 2016, 2017; Aluja et al., 2013; Bachmann et al., 2015; Cancino et al., 2014; Castãnón-Rodriguez et al., 2014; Landeta-Escamilla et al., 2016; Montoya et al., 2000). The future of fruit fly management research will require a continued emphasis on the principles of Integrated Pest Management (IPM) and a broadening of the focus beyond pest control. We highlight several recommendations that may improve future studies on fruit fly management:

- We encourage researchers and technicians to disclose their unpublished knowledge in peer-reviewed journals.
- We encourage researchers and funding organizations to establish and fund long-term studies. The present analysis shows that many tools for monitoring and control tactics showed promising results but need further research to confirm their effectiveness in the field (Chen et al., 2011; Chuang et al., 2014; Goldshtein et al., 2017; Haff et al., 2013).
- More monitoring studies are needed to provide useful knowledge on species detection and population density (Katsoyannos et al., 1999).
- We recommend that the studies include the risk evaluation of the control tactic on non-target species, such as beneficial insects (Cobo et al., 2015).
- We recommend a connection between researchers and commercial companies to meet the current needs of fruit fly management.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.cropro.2018.05.019.

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