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PEST MANAGEMENT

Toxicity and Transgenerational Effects of Insecticides on *Trichopria anastrephae* (Hymenoptera: Diapriidae)

Maíra Chagas Morais[1] · Matheus Rakes[1] · Rafael Antonio Pasini[2] · Anderson Dionei Grützmacher[1] · Dori Edson Nava[3] · Daniel Bernardi[1]

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Abstract

Trichopria anastrephae Costa Lima, 1940 (Hymenoptera: Diapriidae) is a pupal endoparasitoid of *Drosophila suzukii* Matsumura, 1931 (Diptera: Drosophilidae) in Brazil. This species is of great agricultural importance and is almost exclusively managed by organophosphate, spinosyn, pyrethroid, neonicotinoid, and avermectin insecticides. However, frequent application of insecticides can have negative effects on the parasitoid. The objective of this study was to evaluate the lethal and transgenerational toxicity of five insecticides on *T. anastrephae* adults during the F_0, F_1, and F_2 generations. *Drosophila suzukii* puparia were sprayed prior to their exposure to *T. anastrephae* for 24 h. Parameters evaluated in generation F_0 were mortality and rate of parasitism. After the emergence of the F_1 generation, the emergence rate and sex ratio were analyzed. Then, pairs of parasitoids were selected from F_1 and pupae; the host was offered to evaluate parasitism, emergence, and sex ratio of the F_2 generation. In the F_0 generation, malathion was the only insecticide that caused 100% mortality of adults of *T. anastrephae*. However, all insecticides tested affected the parasitism rate, being classified as moderately to slightly harmful. In F_1, the emergence of *T. anastrephae* was also affected, making the insecticides moderately to slightly harmful. However, there were no significant differences in the sex ratio and parasitism rate or the parameters evaluated in F_2, which means that all products were classified as harmless. These results are important for the development of Integrated Management programs for *D. suzukii* and for the conservation of natural populations of *T. anastrephae* in the field.

Keywords Chemical control · biological control · integrated pest management · selectivity · *Drosophila suzukii*

Introduction

Trichopria anastrephae Costa Lima, 1940 (Hymenoptera: Diapriidae) is a parasitoid species endemic to South America (Cruz et al. 2011). It is classified as an idiobiont pupal endoparasitoid and deposits eggs in the hemocoel of fruit fly puparia (Wang et al. 2018; Gonzalez-Cabrera et al. 2019). In Brazil, it has been found on strawberry fruits infested by *Drosophila suzukii* Matsumura, 1931 (Diptera: Drosophilidae) (Wollmann et al. 2016; Andreazza et al. 2017a), a pest insect considered of major agricultural importance in small fruit crops worldwide (Walsh et al. 2011; Calabria et al. 2012; Cini et al. 2012), and in Brazil as of the year 2014 (Deprá et al. 2014; Schlesener et al. 2015; Andreazza et al. 2017b; Dos Santos et al. 2017).

In *D. suzukii* puparia, females of the genus *Trichopria* have the ability to cause the mortality of 100 individuals per generation (Yi et al. 2020). *Trichopria anastrephae* has a life cycle (egg to adult) of approximately 21 days (Krüger et al. 2019; Vieira et al. 2020) and demonstrates a high capacity for interspecific competition with the pupal parasitoid *Pachycrepoideus vindemmiae* Rondani, 1875 (Hymenoptera: Pteromalidae), also on *D. suzukii* pupae (Oliveira et al. 2020).

Because *D. suzukii* larvae have a well-developed immune system, producing a physiological response by increasing the amount of hemocytes and encapsulating the immature

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✉ Daniel Bernardi
dbernardi2004@yahoo.com.br

[1] Department of Plant Protection, Faculty of Agronomy, Federal University of Pelotas, Pelotas, Rio Grande do Sul, Brazil

[2] Riograndense Higher Education Center, Sarandi, Rio Grande do Sul, Brazil

[3] Embrapa Clima Temperado, Pelotas, Rio Grande do Sul, Brazil

stages of larval parasitoids, the use of species such as *Asobara japonica* Belokobylskij, 1998 (Hymenoptera: Braconidae), *Ganaspis brasiliensis* Ihering, 1905, and *Leptopilina* spp. (Hymenoptera: Figitidae) (Poyet et al. 2013; Iacovone et al. 2018; Wang et al. 2021) can become compromised, so the use and conservation of the parasitoid pupal *T. anastrephae* are even more important (Kacsoh and Schlenke 2012).

Although the parasitoid *T. anastrephae* is effective against *D. suzukii* (Krüger et al. 2019; Vieira et al. 2020), chemical control with insecticides broad spectrum, including organophosphates, spinosyns, pyrethroids, neonicotinoids, and avermectins is the most used approach for pest management worldwide (Haye et al. 2016; Andreazza et al. 2017b). In Brazil, spinetoram (spinosyns) is the only insecticide registered for the control of *D. suzukii* to date (Agrofit 2021). In view of this, the insecticides used are those recommended for other fly species, such as *Anastrepha fraterculus* (Wiedemann, 1830) and *Ceratitis capitata* (Wiedemann, 1824) (Diptera: Tephritidae) (Andreazza et al. 2017b; Schlesener et al. 2019; Morais et al. 2021).

While biological control is a promising alternative for *D. suzukii* management (Schetelig et al. 2018; Gonzalez-Cabrera et al. 2019; Krüger et al. 2019; Lee et al. 2019), the frequent application of insecticides each season can have lethal and/or sublethal effects on *T. anastrephae* and also impair the population density and biological performance of the parasitoid over generations (Costa et al. 2014; Beloti et al. 2015; Schlesener et al. 2019; Morales et al. 2020). Therefore, the objective of the present study was to evaluate the lethal (mortality) and transgenerational effects on parasitism, emergence, sex ratio, and survival in F_0, F_1, and F_2 generations of five insecticides widely used in Brazilian fruit growing on *T. anastrephae* adults.

Material and Methods

Insects

Drosophila suzukii was reared on an artificial diet based on cornmeal, yeast, and sugar as proposed by Schlesener et al. (2017). *Trichopria anastrephae* parasitoids were reared and multiplied in *D. suzukii* puparia as per Vieira et al. (2020). Both were kept in a climate-controlled room with a temperature of 25 ± 2 °C, relative humidity of 70 ± 10%, and photophase of 12 h.

Insecticides

We used commercial formulations of five insecticides, representing the main chemical groups used to control arthropod pests of fruit trees grown in Brazil (Table 1). The applied doses followed the recommendations of the manufacturer's package inserts and were diluted in distilled water (Table 1).

Bioassay of toxicity and transgenerational effects

First, 24-h-old *D. suzukii* pupae were separated and deposited on Petri dishes (8-cm diameter) (approximately 150 pupae/treatment). Subsequently, insecticides diluted in distilled water (treatments) were applied by spraying via a calibrated Potter tower to deposit a volume of 1.25 ± 0.25 mg cm^{-2} according to the protocols established by the IOBC (Hassan et al. 2000). Distilled water was used as a negative control. The pupae were kept for one hour on filter paper at a temperature of 25 ± 2 °C and relative humidity of 70 ± 10% to allow evaporation of excess spray. After that time, 15 pupae exposed to the treatments were offered for parasitism to each pair of *T. anastrephae* (aged 24 h) in plastic cages made from acrylic tubes (2.5-cm diameter × 4.5-cm height) closed at the top with *voile* fabric (Vieira et al. 2020). The adults of *T. anastrephae* were fed with pure honey droplets and the pupae were exposed to parasitism for 24 h. After this period, pupae were removed and packed in new acrylic tubes (until emergence, approximately 18 days under bioassay conditions) and *T. anastrephae* pairs were kept in 2.5 cm × 8.5 cm flat-bottomed glass tubes closed at the top with *voile* tissue. The experimental design was entirely randomized, with six treatments and 10 replicates (acrylic tubes) per treatment, with each replicate consisting of a pair of *T. anastrephae*. The biological parameters evaluated were mortality of *T. anastrephae* after 24 h in contact with pupae contaminated by the treatments, pupal parasitism defined by counting emerged

Table 1 Commercial insecticides used to assess lethal and sublethal toxicity in *Trichopria anastrephae*

Active ingredient	Trade name	Insecticide class (IRAC MoA)	Dose	Crop in which are registered
Abamectin	Vertimec 18 EC[a]	Avermectin (6)	75 mL/100 L	Strawberry
Deltamethrin	Decis 25 EC[b]	Pyrethroid (3A)	50 mL/100 L	Citrus, peach, and apple
Malathion	Malathion 1000 EC Cheminova[c]	Organophosphate (1B)	200 mL/100 L	Citrus and peach
Spinetoram	Delegate[d]	Spinosyn (5)	20 g/100 L	Blackberry, raspberry, and blueberry
Thiamethoxam	Actara 250 WG[a]	Neonicotinoid (4A)	10 g/100 L	Strawberry

Manufacturers: [a]Syngenta Crop Protection Ltda, São Paulo, SP, Brazil; [b]Bayer S.A, São Paulo, SP. Brazil; [c]Corteva Agriscience, São Paulo, SP, Brazil; [d]FMC Chemistry do Brazil Ltda, São Paulo, SP, Brazil parasitoids and opening puparia without emergence to verify the presence of *D. suzukii* or *T. anastrephae*, the emergence of parasitoids and sex ratio [Σ♀/Σ (♀ and ♂)].

From the total number of emerged individuals from each treatment (F_1 generation), a minimum of five and a maximum of 15 pairs of *T. anastrephae* were separated and placed in acrylic cages, as mentioned above, and offered 15 pupae of *D. suzukii* (24 h of age) for a period of 24 h. After this time, the parasitoids were removed and placed in new cages (acrylic tubes) and fed with droplets of pure honey to evaluate the survival of males and females. Pupae were placed in an acclimatized room with a temperature of 25 ± 2 °C to evaluate parasitism, emergence, and the sex ratio of F_2 generation *T. anastrephae*.

IOBC classification

To determine toxicity classes, the reduction (R) in parasitism (F_0 and $F_{1)}$ and emergence (F_1 and F_2) was calculated using the equation $R = 100 - [(\text{insecticide treatment value/control value}) \times 100]$, according to Hassan (1994). Then, insecticides were grouped into toxicity classes according to the calculated values based on the criteria established by the International Organization for Biological and Integrated Control (IOBC) (Hassan et al. 2000). The toxicity classes were class 1 = harmless ($R < 30\%$); 2 = slightly harmful ($R = 30$–79%); 3 = moderately harmful ($R = 80$–99%); and 4 = harmful ($R > 99\%$).

Data analysis

The data obtained were tested for normality by the Shapiro–Wilk test and for homogeneity of variance by the Bartlett test. When these assumptions were not met, the data were subjected to non-parametric Kruskal–Wallis analysis of variance, and means were compared using the Dunn test with Bonferroni correction at 5% error probability. For the survival curve, data on the longevity of individuals were used to estimate survival curves using the Kaplan–Meier estimator and comparing the survival curves by the log-rank test through the program SigmaPlot (v.12.5, Systat Software Inc., California, USA). Statistical analyses were performed with R version 4.0.0 software (R Development Core Team 2020).

Results

Toxicity on T. anastrephae and on biological parameters in F_0

When adult parasitoids were exposed to *D. suzukii* pupae treated with insecticides, significant mortality values were observed among the treatments evaluated (Kw = 44.51; df = 5, 54; *p*-value < 0.001) (Table 2). The insecticide malathion showed the highest acute toxicity, causing 100% mortality of *T. anastrephae* adults (Table 2). By contrast, the insecticides deltamethrin and spinetoram caused 60 and 50% mortality of *T. anastrephae*, respectively (Table 2), whereas thiamethoxam and abamectin were statistically similar to the control treatment (Table 2). Regarding parasitism rate, significant differences (Kw = 47.62; df = 5, 54; *p*-value < 0.001) were found in all treatments compared to the control. The lowest parasitism rates were seen for the insecticides malathion ($P = 0.60$ parasitized pupae) and deltamethrin ($P = 1.20$ parasitized pupae) (Table 2). These produced the greatest reductions in parasitism, and thus, malathion (PR = 95.27%) and deltamethrin (PR = 90.50%) were classified as moderately harmful (class 3) (Table 2). Conversely, the insecticides thiamethoxam (RP = 55.11%), spinetoram (RP = 48.81%), and abamectin (RP = 32.28%) were classified as slightly harmful (Class 2) (Table 2).

Transgenerational effects in the F_1 generation

The emergence rate of the F_1 generation of *T. anastrephae* was significantly affected by the tested insecticides (Kw = 46.29; df = 5, 54; *p*-value < 0.001). The control treatment had a mean of 12.20 emerged parasitoids (Table 3), while the lowest emergence rates were caused by the insecticides malathion, with 0.50 parasitoids (SR = 95.90%), and deltamethrin with 1.20 parasitoids (SR = 90.16%) (Table 3), which were thus classified as moderately harmful (class 3). By contrast, the insecticides thiamethoxam (RE = 53.27%) and spinetoram (RE = 48.36%) were classified as slightly

Table 2 Mortality, parasitism rate, parasitism reduction, and IOBC classification for F_0 generation of *Trichopria anastephae* when subjected to different insecticides

Treatment	Mortality (%)	P ($\bar{x} \pm$ SE)[a]	PR(%)[b]	C[c]
Abamectin	10.0 ± 6.66[c]	8.6 ± 0.83[b]	32.2	2
Deltamethrin	60.0 ± 10.00[b]	1.2 ± 0.24[d]	90.5	3
Malathion	100.0 ± 0.00[a]	0.6 ± 0.26[d]	95.2	3
Spinetoram	50.0 ± 0.00[b]	6.5 ± 0.70[b,c]	48.8	2
Thiamethoxam	15.0 ± 10.67[c]	5.7 ± 0.52[c]	55.1	2
Control	0.0 ± 0.00[c]	12.7 ± 0.53[a]	-	-
Kw	44.513	47.6179		
df	5, 54	5, 54		
p-value	< 0.0000001	< 0.0000001		

Means followed by the same letter do not differ statistically by Dunn's test with Bonferroni correction ($p < 0.05$). [a]Evaluation of the number of parasitized pupae in each treatment. [b]Percentage of parasitism reduction compared to control. [c]IOBC classes—class 1: innocuous (PR < 30%); class 2: slightly harmful (30% ≤ PR ≤ 79%); class 3: moderately harmful (80% ≤ PR ≤ 99%); class 4: harmful (PR > 99%)

harmful (class 2) and abamectin (RE = 29.50%) as harmless (class 1) (Table 3). No significant differences were observed in the sex ratio among the treatments (Kw = 9.12; df = 5, 54; *p*-value = 0.10 (Table 3) or with respect to the parasitism rates of the F_1 generation (Kw = 9.94; df = 4, 60; *p*-value = 0.04) (Table 3). Based on the percentage reduction of F_1 parasitism, the insecticides were classified as harmless (class 1) (Table 3).

The survival curves of males and females of the F_1 generation of *T. anastrephae* showed a significant difference between treatments (males: $\chi^2 = 77.4$; df = 4; *p*-value < 0.001, females: $\chi^2 = 77.9$, df = 4, *p*-value < 0.001) (Fig. 1). The insecticides deltamethrin (10.80 days) and thiamethoxam (13.06 days) caused the greatest reductions in male insect survival, relative to the control treatment (29.73 days) (Fig. 1A). The same pattern was observed for *T. anastrephae* females (Fig. 1B). Abamectin did not affect the longevity of males and females of *T. anastrephae* compared to the control treatment (Fig. 1A and B).

Transgenerational effects in the F_2 generation

No significant differences were observed in the emergence rate of *T. anastrephae* in the F_2 generation (Kw = 9.77; df = 4, 60; *p*-value = 0.04) between the treatments evaluated (Table 4). In view of this, all the insecticides evaluated were classified as innocuous (class 1). Similarly, no significant differences were observed in the sex ratio of *T. anastrephae* of the F_2 generation (Kw = 1.49; df = 4, 60; *p*-value = 0.83) (Table 4).

Discussion

Chemical control involving insecticides is an important part of pest arthropod management in Brazilian fruit production. However, the ecological services provided by natural enemies are now receiving due recognition as more sustainable practices are sought. Therefore, studies aiming to evaluate the compatibility between insecticides and natural enemies, within the precepts of IPM, are indispensable (Roubos et al. 2014). In this study, all insecticides tested have neurotoxic effects, and given that there are similarities between the modes of nerve impulse transmission between different animal phyla, they are usually classified as less selective to non-target organisms (Amarasekare et al. 2016; Fontes et al. 2018). The fact was verified about *T. anastrephae* adults in F_0 generation, with emphasis on the organophosphate insecticide.

The highest mortality caused by malathion (F_0 generation of *T. anastrephae*) may have occurred by contact or inhalation during the period of exposure to parasitism, and the lethal impact of this organophosphate insecticide may be attributed to the rapid transformation of oxygenase enzymes, thus inhibiting the action of acetylcholinesterase and other enzyme systems that perform detoxification (Büyükgüzel 2006). These results are similar to those found when *T. anastrephae* adults were exposed to dry insecticide residues via the tarsal contact method (Schlesener et al. 2019) and for the parasitoid *Palmistichus elaeisis* Delvare & LaSalle, 1993 (Hymenoptera: Eulophidae) exposed to the insecticide malathion (100% mortality) (Cruz et al. 2017).

In addition to providing high toxicity on *T. anastrephae* adults, in the F_0 generation, all insecticides significantly affected the rate of parasitism of *T. anastrephae*. This may be attributed to the fact that neurotoxic insecticides affect the neurosecretory system of arthropods, and since reproduction is regulated by hormones, the insecticides may have caused the hormonal imbalance in the insects, interfering in parasitism of the species (Maddrell and Reynolds 1972). Similar results were reported by Fontes et al. (2018) for *Trichogramma achaeae* Nagaraja and Nagarkatti, 1971 (Hymenoptera: Trichogrammatidae) for the insecticides abamectin and

Table 3 Emergence rate and parasitism, emergence reduction and parasitism, sex ratio, and IOBC classification for F_1 generation of *Trichopria anastephae* when subjected to different insecticides

Treatment	E ($\bar{x} \pm$ SE)[a]	ER(%)[b]	C[c]	SR ($\bar{x} \pm$ SE)[d]	P ($\bar{x} \pm$ SE)[e]	PR (%)[b]	C[c]
Abamectin	8.6 ± 0.83[b]	29.5	1	0.6 ± 0.15[a]	10.8 ± 0.50[a]	14.28	1
Deltamethrin	1.2 ± 0.24[d]	90.1	3	0.5 ± 0.15[a]	11.2 ± 1.68[a]	11.11	1
Malathion	0.5 ± 0.22[d]	95.9	3	0.6 ± 0.06[a]	-	-	-
Spinetoram	6.3 ± 0.77[b,c]	48.3	2	0.5 ± 0.09[a]	10.7 ± 0.56[a]	15.24	1
Thiamethoxam	5.7 ± 0.91[c]	53.2	2	0.4 ± 0.09[a]	11.9 ± 0.52[a]	5.76	1
Control	12.2 ± 0.74[a]	-	-	0.6 ± 0.06[a]	12.6 ± 0.28[a]	-	-
Kw	46.2943			9.1217	9.9418		
df	5, 54			5, 54	4, 60		
p-value	< 0.0000001			0.1043	0.04		

Means followed by the same letter do not differ statistically by Dunn's test with Bonferroni correction ($p < 0.05$). [a]Assessment of the number of emerged parasitoids. [b]Emergency reduction (ER) or parasitism reduction (PR) compared to control. [c]IOBC classes—class 1: innocuous (ER or PR < 30%); class 2: slightly harmful (30% ≤ ER or PR ≤ 79%); class 3: moderately harmful (80% ≤ ER or PR ≤ 99%); class 4: harmful (ER or PR > 99%). [d]Sex ratio. [e]Evaluation of the number of parasitized pupae in each treatment

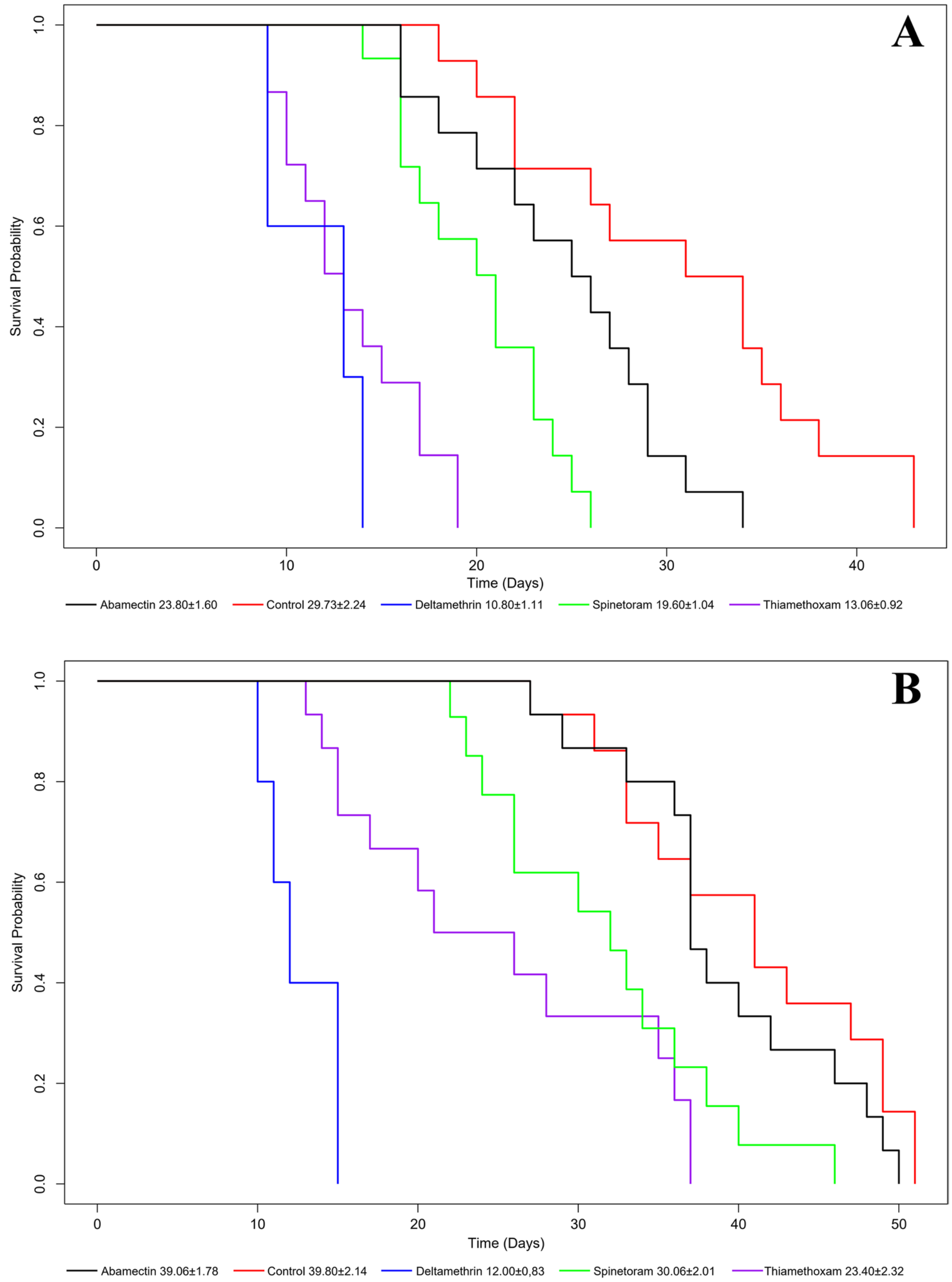

Fig. 1 Survival curve of adults of the F_1 generation of *Trichopria anastrephae*, **A** males and **B** females, when subjected to different insecticides. The curves were generated using Kaplan–Meier estimators and compared using the log-rank test ($P < 0.05$)

thiamethoxam, when sprayed on host eggs. The results for deltamethrin may be directly related to the high toxicity, penetration capacity, and fast action of the product since they act as modulators of sodium channels, causing paralysis and physiological and behavioral changes. The repellent action of this chemical may also have contributed to the reduction of parasitism of *T. anastrephae* (Bos and Masson 1983; Costa et al. 2020). Consequently, the emergence rate of the F_1 generation was also significantly affected, such that malathion and deltamethrin reduced emergence by more than 90%.

Despite their negative effects on the emergence of F_1 generation adults, the insecticides did not affect the sex ratio of *T. anastrephae*. Several studies have shown that agrochemicals products can also cause changes in the sex ratio of beneficial insects. For instance, the organophosphorus insecticide chlorpyrifos modified the sex ratio of the offspring of several Hymenoptera parasitoid (Delpuech and Meyet 2003), whereas imidacloprid significantly changed the sex ratio of the progeny of *Encarsia inaron* Walker (Hymenoptera: Aphelinidae) by increasing the number of male offspring (Sohrabi et al. 2012). However, the mechanisms underlying

Table 4 Emergence rate, emergence reduction, IOBC rating and sex ratio for F_2 generation of *Trichopria anastrephae* when subjected to different insecticides

Treatment	E ($\bar{x} \pm$ SE)[a]	ER (%)[b]	C[c]	SR ($\bar{x} \pm$ SE)[d]
Abamectin	10.7 ± 0.52[a]	12.47	1	0.66 ± 0.06[a]
Deltamethrin	9.8 ± 1.80[a]	19.67	1	0.42 ± 0.17[a]
Spinetoram	9.8 ± 0.65[a]	19.67	1	0.67 ± 0.06[a]
Thiamethoxam	11.2 ± 0.95[a]	8.64	1	0.67 ± 0.04[a]
Control	12.2 ± 0.33[a]	-	-	0.68 ± 0.03[a]
Kw	9.767			1.4904
df	4, 60			4, 60
p-value	0.04			0.8283

Means followed by the same letter do not differ statistically by Dunn's test with Bonferroni correction ($p < 0.05$). [a]Evaluation of the number of emerged parasitoids. [b]Reduction of parasitoid emergence compared to control (ER). [c]IOBC classes—class 1: innocuous (ER < 30%); class 2: slightly harmful (30% ≤ ER ≤ 79%); class 3: moderately harmful (80% ≤ ER ≤ 99%); class 4: harmful (ER > 99%). [d]Sex ratio

the change in the sex ratio of beneficial arthropods caused by insecticides have not been evaluated yet. In the present study, the proportion of the sex ratio of *T. anastrephae* has not changed. This lack of effect on the sex ratio emphasizes the potential of this species as a biological control agent for *D. suzukii*. By contrast, negative effects, as reported by Costa et al. (2014) for *Trichogramma galloi* Zucchi, 1988, would reduce the proportion of females, making it impossible for them to perform their ecological role.

The insecticides deltamethrin and thiamethoxam caused the greatest reductions in the survival of *T. anastrephae*. The active ingredient thiamethoxam, belonging to the neonicotinoid group, is a competitive agonist of nicotinic acetylcholine receptors, being able to induce continuous excitation in neuronal membranes, which results in discharges, paralysis, and the depletion of cellular energy. Pazini et al. (2019) demonstrated similar results regarding the survival of the F_1 generation of *Telenomus podisi* Ashmead, 1893 (Hymenoptera: Platygastridae) when eggs of *Euschistus heros* Fabricius, 1798 (Hemiptera: Pentatomidae) were exposed to thiamethoxam prior to parasitism by F_0. As well as, the effect of deltamethrin on the nervous system of *T. anastrephae* affected adult emergence and subsequent longevity of insects (Garcia et al. 2006). Therefore, the use of deltamethrin-based insecticides in pest management will provide difficulties for the parasitoid to find the host and negatively affect the parasitism of *D. suzukii*.

The F_2 generation of *T. anastrephae* was not affected by any of the treatments, so all insecticides were classified as innocuous at this stage. Similar results were found by Beloti et al. (2015) for *Tamarixia radiata* Waterston, 1922 (Hymenoptera: Eulophidae) when treatments were sprayed on orange tree discs and the F_0 parasitoids remained in contact for 24 h. Likewise, Paiva et al. (2018) reported that when treatments were sprayed on eggs of *Ephestia kuehniella* Zeller, 1879 (Lepidoptera: Pyralidae) prior to parasitism by the F_0 generation of *Trichogramma pretiosum* Riley, 1879 (Hymenoptera: Trichogrammatidae), there were no transgenerational effects on the F_2 generation. However, it is worth noting that the present study was conducted under laboratory conditions, so the parasitoid was exposed to the worst possible conditions. Thus, studies in semi-field and field situations should be conducted since the effects of the environment, such as sunlight (Paiva et al. 2018), can accelerate the degradation of the chemicals and lead to lower acute and sublethal toxicity than in the laboratory setting.

The findings in this study will contribute to the development of IPM programs in which the integration of chemical and biological control is sought of *D. suzukii*; this is because we have the constant occurrence of *T. anastrephae*, a recurrent species in small fruit crops infested by these flies in Brazil (Wollmann et al. 2016, Bernardi et al. 2017). Although the insecticides evaluated in this study (abamectin, deltamethrin, malathion, spinetoram, and thiamethoxam) do not show transgenerational effects on *T. anastrephae*, the use of these products in the management of *D. suzukii* and other arthropod pests that infest the strawberry crop must be used with care, so as not to harm the natural biological control of *D. suzukii* or in a possible mass release program of this parasitoid in the field (Krüger et al. 2019; Vieira et al. 2020). Thus, in areas with the occurrence of *T. anastrephae*, producers should use alternative products, such as plant extracts and essential oils or products based on azadirachtin (De souza et al. 2021), as they do not present toxicity to the parasitoid and are toxic for *D. suzukii* adults.

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Author contribution M.C.M., M.R., R.A.P., and D.B. conducted, analyzed, and wrote the manuscript. A.D.G., D.E.N., and D.B. revised the manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

References

Agrofit. 2021. Sistema de Agrotóxico Fitossanitário. Available from http://agrofit.agricultura.gov.br/agrofit_cons/principal_agrofit_cons. Accessed 06 June 2021.

Amarasekare KG, Shearer PW, Mills NJ (2016) Testing the selectivity of pesticides effects on natural enemies in laboaratory biossays. Biol Control 102:7–16. https://doi.org/10.1016/j.biocontrol.2015.10.015

Andreazza F, Bernardi D, Nava DE, Botton M, Costa VA (2017a) Inimiga Parasitada Cultivar HF 102:20–23

Andreazza F, Bernardi D, Dos Santos RSS, Garcia FRM, Oliveira EE, Botton M, Nava DE (2017) *Drosophila suzukii* in Southern Neotropical Region: current status and future perspectives. Neotrop Entomol 46:591–605. https://doi.org/10.1007/s13744-017-0554-7

Beloti VH, Alves GR, Araújo DFD, Picoli MM, Moral RA, Demétrio CGB, Yamamoto PT (2015) Lethal and sublethal effects of insecticides used on citrus, on the ectoparasitoid *Tamarixia radiata*. PLoS ONE 10:e0132128. https://doi.org/10.1371/journal.pone.0132128

Bernardi D, Ribeiro L, Andreazza F, Neitzke C, Oliveira EE, Botton M, Nava DE, Vendramim JD (2017) Potential use of *Annona* by products to control *Drosophila suzukii* and toxicity to its parasitoid *Trichopria anastrephae*. Ind Crops Prod 110:30–35. https://doi.org/10.1016/j.indcrop.2017.09.004

Bos C, Masson C (1983) Repellent effect of deltamethrinon honey bees. Agronomie 3:545–553

Büyükgüzel K (2006) Malathion-induced oxidative stress in a parasitoid wasp: effect on adult emergence, longevity, fecundity, and oxidative and antioxidative response of *Pimpla turionellae* (Hymenoptera: Ichneumonidae). J Econ Entomol 99:1225–1234

Calabria G, Máca J, Bächli G, Serra L, Pascual M (2012) First records of the potential pest species *Drosophila suzukii* (Diptera: Drosophilidae) in Europe. J Appl Entomol 136:139–147. https://doi.org/10.1111/j.1439-0418.2010.01583.x

Cini A, Ioriatti C, Anfora G (2012) A review of the invasion of *Drosophila suzukii* in Europe and a draft research agenda for integrated pest management. Bull Insectology 65:149–160. https://doi.org/10.1093/humupd/dmu030

Costa MA, Moscardini VF, Gontijo PC, Carvalho GA, Oliveira RL, Oliveira HN (2014) Sublethal and transgenerational effects of insecticides in developing *Trichogramma galloi* (Hymenoptera: Trichogrammatidae). Ecotoxicology 23:1399–1408. https://doi.org/10.1007/s10646-014-1282-y

Costa ESP, Soares MA, Caldeira ZV, Veloso RVS, Silva LA, Silva DJH, Santos ICL, Castro BMC, Zanuncio J, Legaspi JC (2020) Selectivity of deltamethrin doses on *Palmistichus elaeisis* (Hymenoptera: Eulophidae) parasitizing *Tenebrio molitor* (Coleoptera: Tenebrionidae). Sci Rep 10:12395. https://doi.org/10.1038/s41598-020-69200-x

Cruz PP, Neutzling AS, Garcia FRM (2011) Primeiro registro de *Trichopria anastrephae*, parasitoide de moscas-das-frutas, no Rio Grande do Sul. Ciência Rural 41:1297–1299. https://doi.org/10.1590/S0103-84782011000800001

Cruz RA, Zanuncio JC, Lacerda MC, Wilcken CF, Fernandes FL, Tavares WS, Soares MA, Sediyama CS (2017) Side-effects of pesticides on the generalist endoparasitoid *Palmistichus elaeisis* (Hymenoptera: Eulophidae). Sci Rep 7:10064. https://doi.org/10.1038/s41598-017-10462-3

Deprá M, Poppe JL, Schmitz J, De Toni DC, Valente VLS (2014) The first records of the invasive pest *Drosophila suzukii* in the South American continent. J Pest Sci 87:379–383. https://doi.org/10.1007/s10340-014-0591-5

De Souza MT, De Souza MT, Bernardi D, Melo DJ, Zarbin PHG, Zawadneak MAC (2021) Insecticidal and oviposition deterrent effects of essential oils of *Baccharis* spp. and histological assessment against *Drosophila suzukii* (Diptera: Drosophilidae). Sci Rep 11:39–44. https://doi.org/10.1038/s41598-021-83557-7

Delpuech JM, Meyet J (2003) Reduction in the sex ratio of the progeny of a parasitoid wasp *Trichogramma brassicae* surviving the insecticide chlorpyrifos. Arch Environ Contam Toxicol 45:203–208. https://doi.org/10.1007/s00244-002-0146-2

Dos Santos LA, Mendes MF, Krüger AP, Blauth ML, Gottschalk MS, Garcia FRM (2017) Global potential distribution of *Drosophila suzukii* (Diptera, Drosophilidae). PLoS ONE 12:e0174318. https://doi.org/10.1371/journal.pone.0174318

Fontes J, Roja IS, Tavares J, Oliveira L (2018) Lethal and sublethal effects of various pesticides on *Trichogramma achaeae* (Hymenoptera: Trichogrammatidae). J Econ Entomol 111:1219–1226. https://doi.org/10.1093/jee/toy064

Gonzalez-Cabrera J, Contreras-Bermudez Y, Sanchez-Gonzalez JA, Mendoza-Ceballos MY, Arredondo-Bernal HC (2019) Optimization of a wheat germ diet for mass rearing *Drosophila suzukii*. Entomol Exp Appl 166:925–931. https://doi.org/10.1111/eea.12745

Hassan SA (1994) Activities of the IOBC/WPRS working group pesticides and beneficial organisms. IOBC/WPRS Bull 17:1–5

Hassan SA, Halsall N, Gray AP, Kuehner C, Moll M, Bakker FM, Roembke J, Yousef A, Nasr F, Abdelgader H (2000) A laboratory method to evaluate the side effects of plant protection products on *Trichogramma cacoeciae* Marchal (Hym., Trichogrammatidae), pp 107–119. In: M.P. Candolfi, S. Blümel, R. Forster, F.M. Bakker, C. Grimm, S.A. Hassan, U. Heimbach, M.A. Mead-Briggs, B. Reber, R. Schmuck, and H. Vogt (Eds.). Guidelines to evaluate side-effects of plant protection products to non-target arthropods. Gent: IOBC/WPRS.

Haye T, Girod P, Cuthbertson AGS, Wang X, Daane KM, Baroffio C, Zhang J, Desneux N (2016) Current SWD IPM tactics and their practical implementation in fruit crops across different regions around the world. J Pest Sci 89:643–651. https://doi.org/10.1007/s10340-016-0737-8

Garcia P, Cabral S, Oliveira L, Rodrigues A (2006) Effects of deltamethrin on the reproduction of *Trichogramma cordubensis* (Hymenoptera: Trichogrammatidae) Biocontrol Sci Technol 16: 699–708

Iacovone A, Ris N, Poirie M, Gatti JL (2018) Time-course analysis of *Drosophila suzukii* interaction with endoparasitoid wasps evidences a delayed encapsulation response compared to *D. melanogaster*. PLoS One 13:e0201573. https://doi.org/10.1371/journal.pone.0201573

Kacsoh BZ, Schlenke TA (2012) High hemocyte load is associated with increased resistance against parasitoids in *Drosophila suzukii*, a relative of *D. melanogaster*. PLoS ONE 7:1–16. https://doi.org/10.1371/journal.pone.0034721

Krüger AP, Scheunemann T, Vieira JGA, Morais MC, Bernardi D, Nava DE, Garcia FRM (2019) Effects of extrinsic, intraspecific competition and host deprivation on the biology of *Trichopria anastrephae* (Hymenoptera: Diapriidae) reared on *Drosophila suzukii* (Diptera: Drosophilidae). Neotrop Entomol 48:957–965. https://doi.org/10.1007/s13744-019-00705-5

Lee JC, Wang X, Daane KM, Hoelmer KA, Isaacs R, Sial AA, Walton VM (2019) Biological control of spotted-wing *Drosophila* (Diptera: Drosophilidae) – current and pending tactics. J Integr Pest Manag 10:1–9. https://doi.org/10.1093/jipm/pmz012

Maddrell S, Reynolds S (1972) Release of hormones in insects after poisoning with insecticides. Nature 236:404–406. https://doi.org/10.1038/236404a0

Morais MC, Rakes M, Padilha AC, Grützmacher AD, Nava DE, Bernardi O, Bernardi D (2021) Susceptibility of Brazilian populations of *Anastrepha fraterculus*, *Ceratitis capitata* (Diptera: Tephritidae), and *Drosophila suzukii* (Diptera: Drosophilidae) to selected insecticides. J Econ Entomol 114:1291–1297. https://doi.org/10.1093/jee/toab050

Morales SI, Martínez AM, Viñuela E, Figueroa JI, Tamayo F, Rodríguez-Leyva E, Pineda S (2020) Parasitism, host feeding, and transgenerational effects of three insecticides on the eulophid parasitoid *Tamarixia triozae* when exposed in the immature stages. Environ Sci Pollut Res 27:19473–19483. https://doi.org/10.1007/s11356-020-08475-z

Oliveira DC, Stupp P, Martins LN, Wollmann J, Geisler FCS, Cardoso TDN, Bernardi D, Garcia FRM (2020) Interspecific competition in *Trichopria anastrephae* parasitism (Hymenoptera: Diapriidae) and *Pachycrepoideus vindemmiae* (Hymenoptera: Pteromalidae) parasitism on pupae of *Drosophila suzukii* (Diptera: Drosophilidae). Phytoparasitica 49:207–215. https://doi.org/10.1007/s12600-020-00843-2

Paiva ACR, Beloti VH, Yamamoto PT (2018) Sublethal effects of insecticides used in soybean on the parasitoid *Trichogramma pretiosum*. Ecotoxicology 27:448–456. https://doi.org/10.1007/s10646-018-1909-5

Pazini JB, Padilha AC, Cagliari D, Bueno FA, Rakes M, Zotti MJ, Martins JFS, Grützmacher AD (2019) Differential impacts of pesticides on *Euschistus heros* (Hem.: Pentatomidae) and its parasitoid *Telenomus podisi* (Hym.: Platygastridae). Sci Rep 9: 6544. https://doi.org/10.1038/s41598-019-42975-4

Poyet M, Havard S, Precost G, Chabrerie O, Doury G, Gibert P, Eslin P (2013) Resistence of *Drosophila suzukii* to the larval parasitoids *Leptopilina heterotoma* and *Asobara japonica* is related to haemocyte load. Physiol Entomol 38:45–53. https://doi.org/10.1111/phen.12002

R Development Core Team (2020) R - a language and environment for statistical computing. version 4.0.0. http://r-project.org Accessed 11 January 2021.

Roubos CR, Rodriguez-Saona C, Isaacs R (2014) Mitigating the effects of insecticides on arthropod biological control at field and landscape scales. Biol Control 75:28–38. https://doi.org/10.1016/j.biocontrol.2014.01.006

Schetelig MF, Lee KZ, Otto S, Talmann L, Stökl J, Degenkolb T, Vilcinskas A, Halitschke R (2018) Environmentally sustainable pest control options for *Drosophila suzukii*. J Appl Entomol 142:3–17. https://doi.org/10.1111/jen.12469

Schlesener DCH, Wollmann J, Nunes AM, Cordeiro J, Gottschalk MS, Garcia FRM (2015) *Drosophila suzukii:* nova praga para a fruticultura brasileira. Biológico 77:45–51

Schlesener DCH, Wollmann J, Krüger AP, Martins LN, Geisler FCS, Garcia FRM (2017) Rearing method for *Drosophila suzukii* and *Zaprionus indianus* (Diptera: Drosophilidae) on artificial culture media. Drosoph Inf Serv 100:185–189

Schlesener DCH, Wollmann J, Pazini JB, Grützmacher PAC, AD, Garcia FRM, (2019) Insecticide toxicity to *Drosophila suzukii* (Diptera: Drosophilidae) parasitoids: *Trichopria anastrephae* (Hymenoptera: Diapriidae) and *Pachycrepoideus vindemmiae* (Hymenoptera: Pteromalidae). J Econ Entomol 112:1–10. https://doi.org/10.1093/jee/toz033

Sohrabi F, Shishehbor P, Saber M, Mosaddegh MS (2012) Lethal and sublethal effects of buprofezin and imidacloprid on the whitefly parasitoid *Encarsia inaron* (Hymenoptera: Aphelinidae). Crop Prot 32:83–89. https://doi.org/10.1016/j.cropro.2011.10.005

Vieira JGA, Krüger AP, Scheunemann T, Morais MC, Speriogin HJ, Garcia FRM, Nava DE, Bernardi D (2020) Some aspects of the biology of *Trichopria anastrephae* (Hymenoptera: Diapriidae), a resident parasitoid attacking *Drosophila suzukii* (Diptera: Drosophilidae) in Brazil. J Econ Entomol 113:81–87. https://doi.org/10.1093/jee/toz270

Walsh DB, Bolda MP, Goodhue RE, Dreves AJ, Lee J, Bruck DJ, Walton VM, O'Neal SD, Zalom FG (2011) *Drosophila suzukii* (Diptera: Drosophilidae): invasive pest of ripening soft fruit expanding its geographic range and damage potential. J Integr Pest Manag 2:1–7. https://doi.org/10.1603/IPM10010

Wang X, Hogg BN, Hougardy E, Nance AH, Daane KM (2018) Potential competitive outcomes among three solitary larval endoparasitoids as candidate agents for classical biological control of *Drosophila suzukii*. Biol Control 130:18–26. https://doi.org/10.1016/j.biocontrol.2018.12.003

Wang X, Biondi A, Nance AH, Zappalà L, Hoelmer KA, Daane KM (2021) Assessment of *Asobara japonica* as a potential biological control agent for the spotted wing drosophila, *Drosophila suzukii*. Entomol Gen 41:1–12. https://doi.org/10.1127/entomologia/2020/1100

Wollmann J, Schlesener DCH, Ferreira MS, Garcia MS, Costa VA, Garcia FRM (2016) Parasitoids of Drosophilidae with potential for parasitism on *Drosophila suzukii* in Brazil. Drosoph Inf Serv 99:38–42

Yi C, Cai P, Lin J, Liu X, Ao G, Zhang Q, Xia H, Yang J, Ji Q (2020) Life history and host preference of *Trichopria drosophilae* from southern China, one of the effective pupal parasitoids on the *Drosophila* species. Insects 11:103. https://doi.org/10.3390/insects11020103