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Toxicity and residual effect of selected insecticides against Bemisia tabaci and Orius tristicolor

Toxicidade e efeito residual de inseticidas selecionados contra Bemisia tabaci e Orius tristicolor

Toxicidad y efecto residual de insecticidas seleccionados contra Bemisia tabaci y Orius tristicolor

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Abstract
The whitefly *Bemisia tabaci* is a global pest, well-known for its capacity to transmit begomoviruses during sap sucking (<24h). Chemical control is mainly adopted, aiming to kill the insect before it acquires and transmits virus. In the present study, we evaluated the toxicity of 17 insecticides on *B. tabaci* and subsequently determined the lethal time for this pest (only for the insecticides that caused *B. tabaci* mortality equal to or greater than 80%). Here, we present an efficient methodology for assessing the toxicity in the individual adult. We also provided an investigation regarding the residual effect of insecticides to control *B. tabaci* on cabbage in greenhouses. The selectivity of these insecticides for the predator minute pirate bug *Orius tristicolor* was also assessed. Bifenthrin, cartap, chlorfenapyr and chlorpyrifos caused ≥ 80% mortality on whitefly adults. They also showed fast lethal effect (<24 h), principally cartap, which caused 100% of mortality in only 45 min. However, these insecticides showed a short residual period of whitefly control (<3 days) and did not present physiological selectivity for O. tristicolor. In terms of whitefly management, only a few insecticides were efficient to avoid begomoviruse transmission. The short residual period and the absence of physiological selectivity for the predator suggests that the use of these products should involve a sustainable approach. Taking pest population levels into account when making control decisions and for predator preservation in the agroecosystems should positively contribute to more sustainable whitefly management.
Keywords: Whitefly; Pirate bug; Insecticide toxicity; Selectivity of insecticides; Residual period of control.

Resumo
A mosca-branca *Bemisia tabaci* é uma praga mundial, conhecida por sua capacidade de transmitir begomovírus durante a sucção de seiva (<24h). O controle químico é adotado principalmente, visando matar o inseto antes que ele adquira e transmita o vírus. No presente estudo, foi avaliado a toxicidade de 17 inseticidas sobre *B. tabaci* e posteriormente determinamos o tempo letal para esta praga (somente para os inseticidas que causaram mortalidade de *B. tabaci* igual ou superior a 80%). Aqui, apresentamos uma metodologia eficiente para avaliar a toxicidade no adulto individual. Também fornecemos uma investigação sobre o efeito residual de inseticidas no controle de *B. tabaci* em

repolho em casa de vegetação. A seletividade desses inseticidas para o percevejo predador *Orius tristicolor* também foi avaliada. Bifentrina, cartape, clorfenapir e clorpirifós causaram ≥ 80% de mortalidade em adultos de mosca branca. Eles também mostraram efeito letal rápido (<24 h), principalmente o cartape, que causou 100% de mortalidade em apenas 45 min. No entanto, esses inseticidas apresentaram curto período residual de controle da mosca-branca (<3 dias) e não apresentaram seletividade fisiológica para O. tristicolor. Em termos de manejo da mosca-branca, poucos inseticidas foram eficientes para evitar a transmissão de begomovírus. O curto período residual e a ausência de seletividade fisiológica para o predador sugerem que o uso desses produtos deve envolver uma abordagem sustentável. Levar em consideração os níveis populacionais de pragas ao tomar decisões de controle e preservação de predadores nos agroecossistemas deve contribuir positivamente para um manejo mais sustentável da mosca-branca.
Palavras-chave: Mosca branca; Mercevejo predador; Toxicidade inseticida; Seletividade de inseticidas; Período residual de controle.

Resumen

La mosca blanca *Bemisia tabaci* es una plaga mundial, conocida por su capacidad de transmitir begomovirus durante la succión de savia (<24h). Se adopta principalmente el control químico, con el objetivo de matar al insecto antes de que adquiera y transmita el virus. En el presente estudio se evaluó la toxicidad de 17 insecticidas sobre *B. tabaci* y posteriormente se determinó el tiempo letal para esta plaga (solo para aquellos insecticidas que provocaron una mortalidad de *B. tabaci* igual o superior al 80%). Aquí, presentamos una metodología eficiente para evaluar la toxicidad de adultos individuales. También proporcionamos una investigación sobre el efecto residual de los insecticidas en el control de *B. tabaci* en el repollo en un invernadero. También se evaluó la selectividad de estos insecticidas para la chinche depredadora *Orius tristicolor*. Bifentrina, cartape, clorfenapir y clorpirifos causaron ≥ 80% de mortalidad en mosca blanca adulta. También mostraron un efecto letal rápido (<24 h), especialmente el cartap, que causó el 100% de mortalidad en solo 45 min. Sin embargo, estos insecticidas mostraron un corto período residual de control de mosca blanca (<3 días) y no mostraron selectividad fisiológica para O. tristicolor. En cuanto al manejo de la mosca blanca, pocos insecticidas fueron efectivos para prevenir la transmisión de begomovirus. El corto período residual y la ausencia de selectividad fisiológica por el depredador sugieren que el uso de estos productos debe implicar un enfoque sostenible. Tener en cuenta los niveles de población de plagas al tomar decisiones para controlar y preservar a los depredadores en los agroecosistemas debería contribuir positivamente a un manejo más sostenible de la mosca blanca.
Palabras clave: Mosca blanca; Chinche de cama depredador; Toxicidad insecticida; Selectividad de insecticidas; Período residual de control.

1. Introduction

The whitefly *Bemisia tabaci* (Genn.) (Hemiptera: Aleyrodidae) is a sap sucking insect of global importance causing high yield losses in many crops such as cotton, soybeans, beans, tomatoes, potatoes, brassicas, cucurbitis and asteraces (Naranjo et al. 2009; Barbosa et al. 2014; Masuda et al. 2016; Vandervoet et al. 2018). *B. tabaci* is a polyphagous species that has more than 700 host plants and is found on all continents of the planet (Barro et al. 2011; Li et al. 2011; Abdelkrim et al. 2017). The damage caused by *B. tabaci* is due to sap sucking, injection of toxins and transmission of viruses. Additionally, a sooty mold affects the plant photosynthesis, this opportunistic fungi occurs on the plant surface due to the honeydew excreted by these insects (Barbosa et al. 2014; Chu et al. 2010). Both *B. tabaci* nymphs and adults cause damage to the plants. However, the greatest damage is caused by adults because they are vectors of begomoviruse of economic importance and can transmit this viruses during sap feeding (Abdelkrim et al. 2017; Fang et al. 2013; Gilbertson et al. 2015).

Insecticide use is the main pest control method employed in agroecosystems for reduce pest populations (including *B. tabaci*) before they cause economic damage to crops (Naveen et al. 2017; Roditakis et al. 2017; Ramos et al. 2017). For the control of severe infestations, it is also important to select efficient, fast acting insecticides, since *B. tabaci* has shown a significant ability to cause economic damage to crops. This is even more important to control insects that are disease vectors (e.g. *B. tabaci*), therefore fast-acting control is an important strategy to avoid proliferation of pathogens in crops (Gilbertson et al. 2015; Roditakis et al. 2017). In this context, the period of acquisition and viral transmission to plants by *B. tabaci* is about 24 hours each (Mehta et al. 1994; Smith & Giurcanu 2014). Thus, it is important that insecticide control measures for *B. tabaci*

are realized within a period of less than 24 hours after sprayed an insecticide, to enable the control of this pest before it acquires or transmits viruses to other plants.

For pest management using chemical control, knowledge of insecticides' residual period of control for these organisms is also important. This period consists in the time after insecticide application during which the insecticide continues to control the pest (Araújo et al. 2017). Insecticides with longer residual periods require a lower frequency of application, which reduces pest control costs and the environmental impact of these pesticides on non-target organisms. In addition to efficiency, lethal time and the residual period of control, it is important to be aware of the selectivity of insecticides for non-target organisms, especially natural enemies (Ramos et al. 2017; 2018; Pereira et al. 2017). Knowledge of the selectivity of insecticides makes it possible to reduce their impact on natural enemies populations (Araújo et al. 2017; Bacci et al. 2009). The selectivity of insecticides for natural enemies is grouped into two categories: physiological and ecological selectivity (Ripper et al. 1951). Physiological selectivity consists of the use of insecticides that are more toxic for the pest than for natural enemies (Ramos et al. 2018; 2017; Pereira et al. 2017; Bacci et al. 2009; Ripper et al., 1951). Ecological selectivity is obtained through the application of insecticides to reduce the exposure of natural enemies to these products (Ramos et al. 2017; Bacci et al. 2009; Ripper et al. 1951).

In the 1980s, the chemical control of *B. tabaci* was performed using organochlorine, organophosphorus, carbamate and pyrethroid insecticides (Naveen et al. 2017; Sharaf 1986). From the 1990s, the control of *B. tabaci* adults began to be performed using neonicotinoid insecticides while the control of their nymphs was carried out with growth regulator insecticides (Naveen et al. 2017; Horowitz et al. 2002; Jeschke et al. 2010). Currently, even with frequent insecticide use to control *B. tabaci*, failures in this pest control in various regions around the world have been reported (Barbosa et al. 2014; Roditakis et al. 2017; Marasinghe et al. 2017; Dângelo et al. 2018). These control failures may occur due to the selection of resistant populations or operational problems related to the application technology for these pesticides (Silva et al. 2011; Gontijo et al. 2013; Garcerá et al. 2014).

Predatory pirate bugs feature among the main natural enemies of *B. tabaci*. The pirate bug (Hemiptera: Anthocoridae) has global importance in the biological control of whiteflies, mites, aphids, thrips and lepidopterans eggs and small larvae (Chow et al. 2010; Nemec et al. 2016; Zhao et al. 2017; Banihashemi et al. 2017). Among the species of anthocorid pirate bugs is *Orius tristicolor* (White) (Hemiptera: Anthocoridae), a predator that has been reported acting as a biological control agent in countries belonging to all five biogeographical regions of the globe (CABI 2018).

A current challenge for whitefly integrated pest management (IPM) programs is to provide an efficient management of this pest that allows the conservation of their natural enemies. In this sense, many studies regarding the toxicity of pesticides for *B. tabaci* and their natural enemies have been reported (Dângelo et al. 2018; Horowitz et al. 2002; Marasinghe et al. 2017; Roditakis et al. 2017). However, many of these studies did not consider some of the most promising insecticides registered for control the whitefly such as acetamiprid, chlorfenapyr, imidacloprid, and thiamethoxam. In addition, few methodologies are efficient in assessing the toxicity response in the individuals adults. Therefore, through an efficient methodology, in the present study, we aimed to determine the commercial insecticides' (i) efficiency, (ii) lethal time and (iii) residual period of control for *B. tabaci* adults, and (iv) their physiological selectivity for the predator *O. tristicolor*.

2. Methodology

Plants

Cabbage plants *Brassica oleracea* (sacaia hybrid) were grown in a greenhouse at the campus of the Universidade Federal de Viçosa (UFV), Viçosa, MG, Brazil (20° 48' 45 " S, 42° 56' 15" W; 600 m altitude; tropical climate). The plants were cultivated in 5 L plastic pots using standard practices without pesticide application (FAO 2002).

Insects

Whiteflies and *O. tristicolor* adults used in the bioassays were obtained from laboratory colonies. Laboratory colonies were established using individuals collected from cabbage fields in Viçosa county. *B. tabaci* individuals were established and maintained on cabbage plants placed in wooden cages covered by organza cloth (45 × 45 × 45 cm). Molecular analyses showed that these *B. tabaci* individuals belong to biotype B (Brown et al. 2000; Lisha et al. 2003). The rearing of *O. tristicolor* was established according to the methodology described by Ramos et al. (2017). *O. tristicolor* nymphs were placed in Petri dishes (9 × 2 cm) containing pieces of paper to serve as shelter. *Ephestia kuehniella* Zeller (Lepidoptera: Pyralidae) eggs were provided every 2 days *ad libi*tum for the nymphs and adults' feeding, and wet cotton was provided for hydration. *O. tristicolor* adults were maintained in glass jars (1 L) with pieces of paper, eggs (*E. kuehniella*), wet cotton and *Bidens pilosa* L. (Asterales: Asteraceae) flowers as an oviposition substrate used for mass rearing of pirate bugs (Ramos et al. 2017; Pereira et al. 2017). All colonies and bioassays were maintained at 25 ± 1 °C and relative humidity of 75 ± 5% under a 12:12 h photoperiod.

Insecticides

The insecticides used and their recommended field rate are described in Table 1. The insecticides adopted in this study belong to different chemical groups widely used for whitefly management. For the bioassays, recommended field rates were adopted for the insecticides (MAPA 2014). The spreader–sticker nonylphenol polyethylene glycol ether 125 SC (Milenia Agro Ciências SA, Londrina, Brazil) was included in all treatments at a concentration of 1 mL.L^{-1}. In all bioassays, the control consisted of water and spreader–sticker.

Table 1 - Commercial insecticides used in the bioassays.

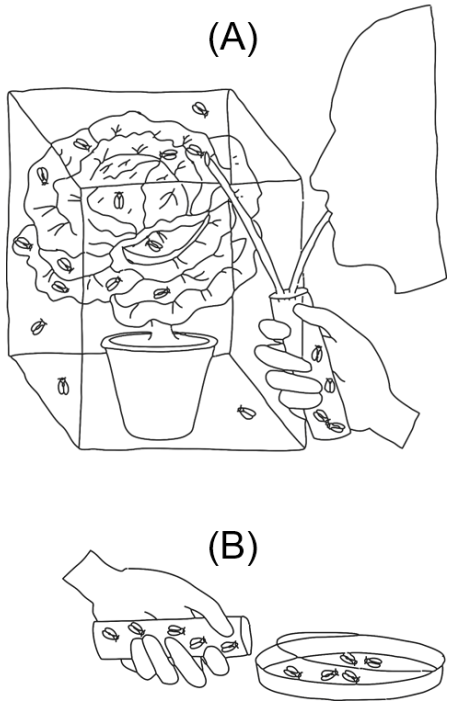
Insecticide	Chemical group	Manufacturer	Rate* (mg a.i. mL^{-1})
Acephate 750 SP	Organophosphate	Arysta	3.75
Acetamiprid 200 SP	Neonicotinoid	Iharabrás	0.20
Alpha-cypermethrin 100 SC	Pyrethroid	Basf	0.20
Beta-cyfluthrin 125 EC	Pyrethroid	Bayer	0.031
Beta-cipermetrina 100 EC	Pyrethroid	Arysta	0.25
Bifenthrin 100 EC	Pyrethroid	FMC	0.50
Cartap 500 SP	Nereistoxin analogue	Iharabrás	1.25
Cypermethrin 200 CS	Pyrethroid	FMC	0.60
Chlorfenapyr 240 SC	Pyrrole analogue	Basf	2.40
Chlorpyrifos 480 EC	Organophosphate	Helm	3.00
Deltametrin 25 EC	Pyrethroid	Bayer	0.03
Esfenvalerate 25 EC	Pyrethroid	Sumitomo	0.05
Fenpropathrin 300 EC	Organophosphate	Sumitomo	0.60
Gamma-cyhalothrin 150 EC	Pyrethroid	Cheminova	0.05
Imidacloprid 700 WG	Neonicotinoid	Helm	0.875
Lambda-cyhalothrin 50 CS	Pyrethroid	Syngenta	0.30
Thiamethoxam 250 WG	Neonicotinoid	Syngenta	0.05

* a.i. = active ingredient. Source: Authors.

Insecticide efficiency bioassay

To assess the insecticide efficiency for controlling *B. tabaci*, 17 insecticides were tested. This bioassay was performed with a completely randomized design with six replicates for each treatment (insecticides at recommended field doses and the control). Each replicate consisted of a Petri dish (9 x 2 cm) containing a treated cabbage leaf disk (9 cm) and 20 whiteflies (adults). Cabbage leaf disks were immersed for 5s in each treatment solution. After drying in the shade for 2h, leaf disks were placed in a Petri dish. For the insects' transference, 10 whiteflies (adults) for each time, they were sucked for a device compound of two hoses coupled to an acrylic container (Figure 1A).

Figure 1 - Scheme showing the efficient methodology for assessing the toxicity of *Bemisia tabaci* adults.



Source: Authors.

Subsequently, this device was opened and these 10 individuals were placed in the Petri dish (Fig. 1B). A clear plastic film (Parafilm®) containing holes made by pins nº 24 was used to cover each Petri dish and allow gas exchange. Insect mortality was evaluated 24 hours after *B. tabaci* exposure to treatments. Insects that remained stationary for more than 10 seconds after being touched with a fine-bristled brush were considered dead (Ramos et al. 2017).

Insecticide time-mortality response bioassay

For this bioassay, we selected the insecticides from the previous bioassay that caused *B. tabaci* mortality equal to or greater than 80%. This mortality threshold was adopted because it is the mortality rate indicated by Brazilian legislation to consider an insecticide efficient, thereby allowing its registration (Ramos et al. 2017; Silva et al. 2011; Gontijo et al. 2013; Robertson et al. 2017). Therefore, to determine the lethal time, four insecticides (bifenthrin, cartap, chlorfenapyr and chlorpyrifos) were tested. In this bioassay, each replicate consisted of an individual whitefly adult. Each treatment (insecticides and control) consisted of six Petri dishes, with each Petri dish (9 × 2 cm) containing a treated cabbage leaf disk (9 cm) and 20 whiteflies (adults). The experimental procedure for the treatment was the same as that described in the previous bioassay. The survival of *B. tabaci* adults was subsequently monitored to determine the appropriate time intervals for insect mortality

assessments for each treatment. For the insecticides bifenthrin, chlorfenapyr, and control, mortality was assessed every 1 h until all insects had died. For the insecticide chlorpyrifos, mortality was assessed every 30 min, while for the insecticide cartap, mortality was assessed every 5 min until all insects were dead. Insects were considered dead when they remained stationary for more than 10 seconds after being touched with a fine-bristled brush (Ramos et al. 2017).

Insecticide residual period of control bioassay

The treatments used in this bioassay were the insecticides (bifenthrin, cartap, chlorfenapyr and chlorpyrifos) that caused *B. tabaci* mortality above 80%. This bioassay was carried out at the UFV campus from March 2015 to May 2015. In this bioassay, 25 cabbage plants were used, which were cultivated in 5 L plastic pots (1 plant/pot) employing standard practices without pesticide application (FAO 2002). For insecticide spraying, a CO_2 pressurized backpack sprayer was used, at 3.1 bar pressure, a flow rate of 240 L ha^{-1}, and with an MGA 8002 tip-type (Magnojet, Commercial Industry of Agricultural Products LTDA, Paraná-PR, Brazil). The experimental design was in randomized blocks with five replications, with each replicate consisting of one plant. Cabbage plants were transplanted (10 leaves/plant) after 30 days. The plants were sprayed according to the treatments (insecticides and control). After spraying, the plants were allowed to dry in the shade for 2h and kept in a greenhouse. New leaves that grew after insecticide spraying were not used in this bioassay.

B. tabaci adults were placed in contact with cabbage leaf disks (9 cm) that were sprayed with insecticide or control after 0, 2, 5, 11, 17, 22 and 27 days. Leaves from the sprayed plants were collected randomly on the indicated days and placed in Petri dishes (9 x 2 cm). Each treatment (insecticide and control) consisted of six Petri dishes, with each Petri dish (9 x 2 cm) containing a treated cabbage leaf disk (9 cm) and 20 whiteflies (adults). A clear plastic film (Parafilm®) containing holes made using nº 24 pins was used to cover each Petri dish and allow gas exchange. Insect mortality was evaluated 24 hours after *B. tabaci* exposure to treatments. Insects were considered dead when they remained stationary for more than 10 seconds after being touched with a fine-bristled brush (Ramos et al. 2017).

Insecticide physiological selectivity bioassay

To assess the physiological selectivity of insecticides for the pirate bug *O. tristicolor*, four insecticides, bifenthrin, cartap, chlorfenapyr and chlorpyrifos, were tested. These were the insecticides that caused *B. tabaci* mortality above 80% in the insecticide efficiency bioassay. For the physiological selectivity bioassay, the experimental design was completely randomized with six replicates for each treatment. Each replicate included a Petri dish (9 x 2 cm) containing a treated cabbage leaf disk and 20 non-sexed pirate bug adults. Additionally, food, in the form of approximately 80 *E. kuehniella* eggs was provided for the pirate bugs, and water in a piece of moistened cotton, according to the methodology described by Ramos et al. (2017). The mortality assessment was performed 24 h after insecticide exposure using the same criteria as those for the insecticide efficiency bioassay for *B. tabaci* for comparative purposes. Pirate bugs were considered dead if they did not walk more than 10 seconds after being prodded with a fine-bristled brush (Ramos et al. 2017).

Statistical analyses

Insect mortality caused by insecticides was corrected in relation to the mortality caused by the control using Abbott's formula (1925). In the insecticide efficiency bioassay, the corrected *B. tabaci* mortality data was submitted to Student's *t*-test ($P < 0.05$). The Insecticides were considered efficient if they caused mortality equal to or greater than 80%, according to Brazilian legislation (Ramos et al. 2017; Silva et al. 2011; Gontijo et al. 2013; Robertson et al., 2017).

Based on *B. tabaci* mortality data from the insecticide lethal time bioassay, a survival rate at each evaluation time, for each treatment was calculated, for use in the survival analysis. The experimental data was subjected to a survival analysis using

Kaplan-Meier product-limit method with the SAS LIFETEST procedure (SAS 2013). From this analysis, time-mortality curves for *B. tabaci* adults for each insecticide and control were estimated.

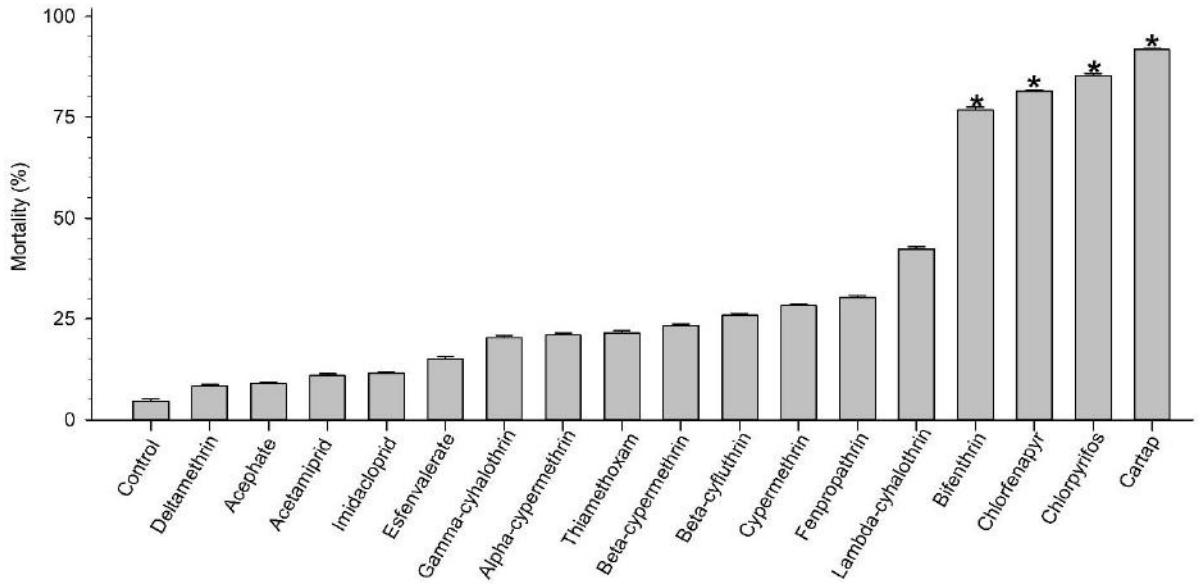
The corrected mortality for *B. tabaci* adults as a function of time after each insecticide spraying, from the insecticide residual period of control bioassay, were submitted to regression analysis ($P < 0.05$). A logistic regression model for dose-response (parameters *a*, *b*, *c* and *d*) was used, represented by the equation $Y = a + b\ [1 + (X/c)d\ ]$-1, where $Y = B.\ tabaci$ mortality (%) and X = time after spraying (days) (Araújo et al. 2017; Vásquez-Castro et al. 2012). The residual period of control was defined as the period after spraying when the pesticide continues to cause pest mortality of ≥80% (Araújo et al. 2017). *O. tristicolor* and *B. tabaci* corrected mortality data was evaluated using Student's *t*-test ($P < 0.05$). When the same insecticide caused higher mortality for the predator than for the pest, it was considered as not presenting physiological selectivity for the predator (Ramos et al. 2017; Pereira et al. 2017; Bacci et al. 2009).

3. Results

***Efficiency of insecticidal control of** B. tabaci*

Two insecticide categories were found, based on the mortality threshold equal to or higher than 80% required by Brazilian legislation to define insecticide efficiency. First, the insecticides bifenthrin, cartap, chlorfenapyr and chlorpyrifos caused ≥ 80% mortality, and thus, were considered efficient insecticides to control *B. tabaci* adults. Secondly, the insecticides acephate, acetamiprid, alpha-cypermethrin, beta-cyfluthrin, beta-cypermethrin, cypermethrin, deltamethrin, esfenvalerate, fenpropathrin, gamma-cyhalothrin, imidacloprid, lambda-cyhalothrin and thiamethoxam caused mortality ranging from 8.35 to 42.29%, that is, mortality < 80%. Therefore, these insecticides were considered inefficient to control *B. tabaci* adults (Figure 2).

Figure 2 - Mortality (mean ± standard error) of adult *Bemisia tabaci* exposed to the control and recommended doses of 17 insecticides. *Histogram bars with an asterisk indicate that the mortality caused by the insecticide is ≥ 80% by Student's *t*-test at $P < 0.05$.

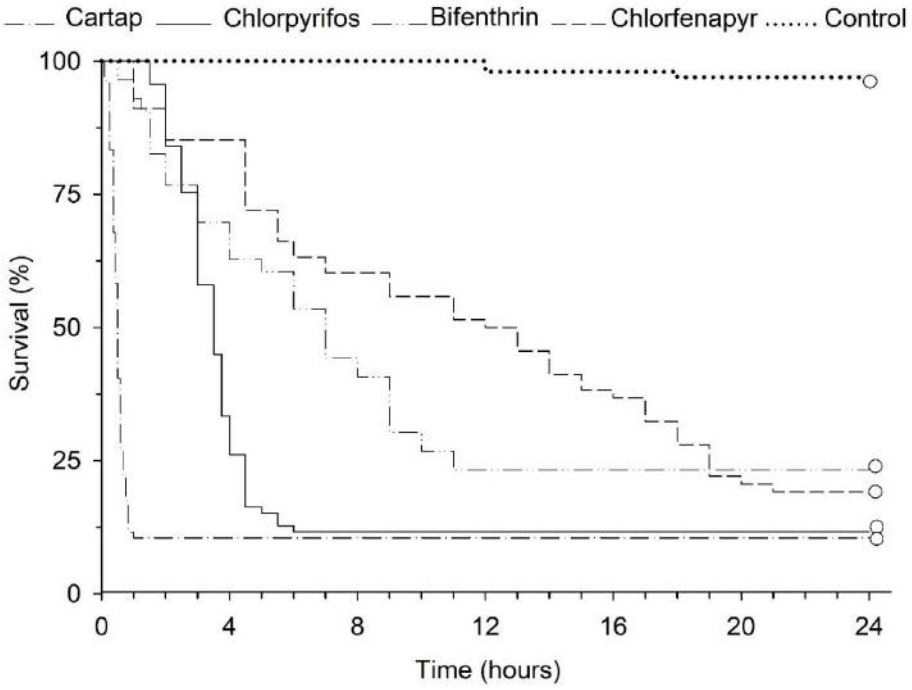


Source: Authors.

***Time-mortality for insecticide response of** B. tabaci*

The mortality time for insecticide response (survival) of *B. tabaci* when exposed to insecticides was significantly different between the insecticide treatments (log-rank test, χ^2 = 451.34, d.f. = 4, P <0.0001). We observed that all the efficient insecticides caused up to 80% mortality of *B. tabaci* adults less than 24 hours after exposure to the treatments. Cartap caused up to 80% mortality of *B. tabaci* adults within only 45 minutes whereas chlorpyrifos caused 80% mortality within 4 hours. The insecticide bifenthrin caused up to 80% mortality after 11 hours, followed by the insecticide chlorfenapyr that caused 80% mortality in *B. tabaci* after 19 hours (Figuer 3).

Figure 3 - Survival curves estimated using the product-limit Kaplan-Meier method. *Bemisia tabaci* adults in the control and exposed to the recommended field dose of the four insecticides.

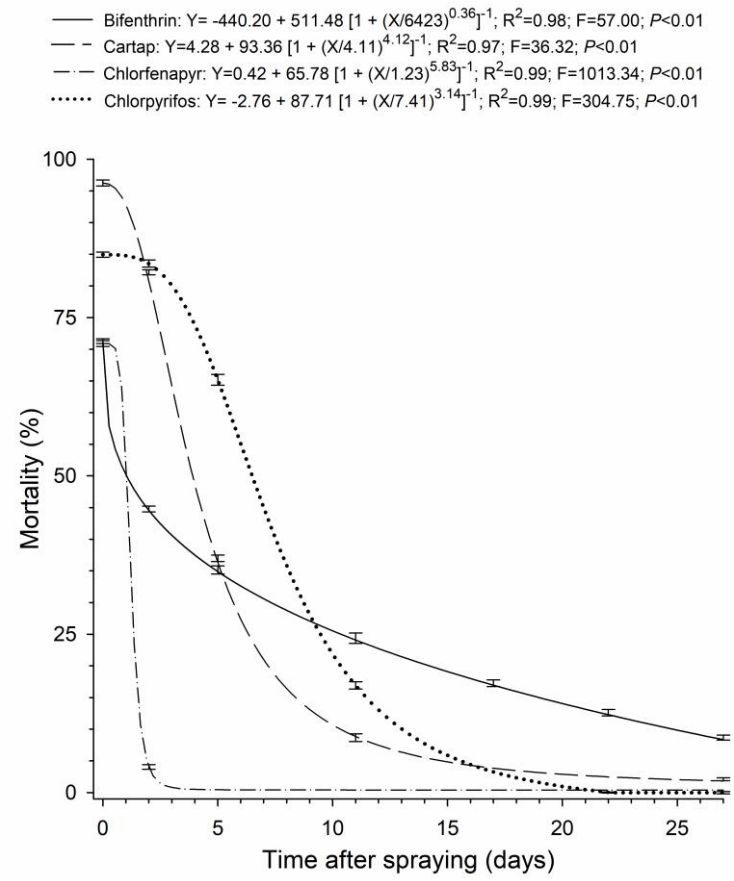


Source: Authors.

***Residual period of control of** B. tabaci*

Regression models, with significance (P < 0.05), relating *B. tabaci* mortality as a function of time after insecticide spraying in cabbage plants, were obtained (Figure 4).

Figure 4 - Mortality curves (mean ± confidence interval) of *Bemisia tabaci* adults as a function of time after spraying four insecticides.



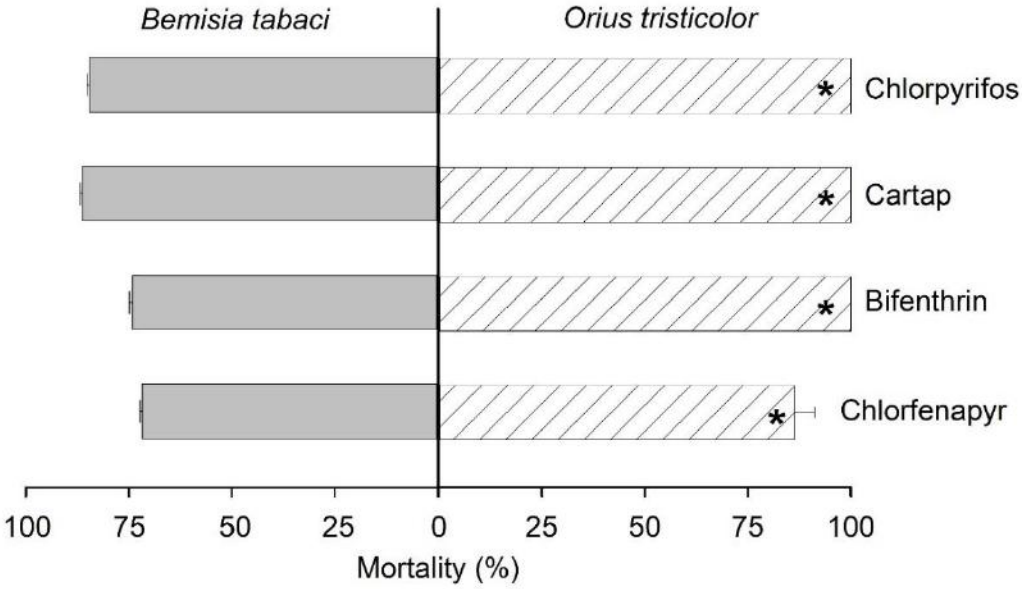
Source: Authors.

We can observe that all insecticides tested showed decreased mortality over time. However, the residual period of control of each insecticide (mortality ≥ 80%) showed different decreasing patterns. After 2 days of spraying, bifenthrin and chlorfenapyr showed the lowest residual period of control of *B. tabaci*, that is, they caused mortality lower than 80% after 2 days. The insecticides cartap and chlorpyrifos displayed a residual period of control of only 3 days. Overall, the treatments did not present efficient *B. tabaci* control (mortality ≥ 80%) for more than 4 days.

***Selectivity of insecticides for the predator** O. tristicolor*

Among all the insecticides tested, bifenthrin, cartap, chlorpyrifos and chlorfenapyr, caused greater mortality in the predator *O. tristicolor* than in *B. tabaci*. The mortality caused by these insecticide treatments in the predator *O. tristicolor* ranged from 86 to 100%, with bifenthrin, cartap and chlorpyrifos standing out, causing 100% mortality. Therefore, no insecticide tested showed physiological selectivity for the predator (Figure 5).

Figure 5 - Mortality (mean ± standard error) of *Bemisia tabaci* adults and the predator *Orius tristicolor* exposed to the recommended field dose of the four insecticides. *Histogram bars with an asterisk indicate that the mortality caused by the same insecticide is significantly higher for *O. tristicolor* than for *B. tabaci* by Student's *t*-test at $P < 0.05$.



Source: Authors.

4. Discussion

The insecticides bifenthrin, cartap, chlorfenapyr and chlorpyrifos showed high toxicity for *B. tabaci* adults, presenting efficient control (mortality ≥ 80%). These four insecticides represent four different modes of action, including a sodium channel modulator (bifenthrin), a channel blocker of nicotinic acetylcholine receptors (cartap), a decoupler of oxidative phosphorylation via disruption of the proton (chlorfenapyr), and an acetylcholinesterase inhibitor (chlorpyrifos) (Ramos et al. 2017; Araújo et al. 2017; Matsumura 1985). The use of these products to rotate the active principle can contribute to IPM programs, controlling the pest and helping to manage insecticide resistance (Dângelo et al. 2018; Silva et al. 2011). Prolonged and repeated use of the same mode of action leads to selection of resistant populations and reduction in insecticides' efficiency (Marasinghe et al. 2017; Dângelo et al. 2018). Therefore, the use of insecticides with different modes of action reduces the selection of resistant individuals, and consequently, mitigates problems with pest resistance (Ramos et al. 2017; Silva et al. 2011).

Most of the insecticides tested were not efficient to control *B. tabaci* adults (mortality < 80%). In fact, these insecticides caused mortality below 43%. Neonicotinoids (acetamiprid, imidacloprid, and thiamethoxam), organophosphorus (acephate) and pyrethroids (alpha-cypermethrin, beta-cyfluthrin, beta-cypermethrin, and cypermethrin) were included among the insecticides that were inefficient in controlling *B. tabaci* adults. The low *B. tabaci* mortality (< 80%) with these insecticides could indicate chemical control failures, which have also been reported by several other studies (Naveen et al. 2017; Marasinghe et al. 2017; Dângelo et al. 2018). Control failures suggest problems related to product application technology and the resistance of pest populations to insecticides (Silva et al. 2011; Gontijo et al. 2013; Garcerá et al. 2014). In this study, the methodology of insecticide laboratory application and exposure maximizes insecticide toxicity at the same time as providing more complete coverage of the leaves and insect contact with the insecticide, in addition to reducing insecticide breakdown. Therefore, our results provide support for the idea that the low mortality rates observed in this study were due to the resistance of this pest to insecticides (Naveen et al. 2017; Ramos et al. 2017; Garcerá et al. 2014).

B. tabaci resistance to insecticides probably encompasses the main product groups used in control of adults of this pest. Products that presented a high mortality rate (≥80%) for the pest, were found among the pyrethroids and organophosphates, while other products from these groups showed low mortality. It is assumed that the resistance of *B. tabaci* is not generalized to all the insecticides of the same group. Different levels of resistance between the pyrethroids have been reported, such as in the case of the insecticides bifenthrin and beta-cypermethrin for Asian and Mediterranean *B. tabaci* populations (Qu et al. 2017). Among the insecticides containing organophosphorus, a single *B. tabaci* population that expresses resistance to the insecticide monocrotophos and susceptibility to the insecticides triazophos and chlorpyrifos has been found (Naveen et al. 2017). Therefore, we once again underline the importance of adopting active principle rotation of products for the management of whitefly resistance in the crops, so that efficient products remain an alternative for use in whitefly management.

For control of severe infestations such as *B. tabaci*, the application of fast-acting insecticides is recommended to avoid these organisms causing economic damage in the crops (Ramos et al. 2017; de Freitas et al. 2011). For insects that are pathogen vectors such as *B. tabaci*, this fast-acting insecticide control is even more desirable to prevent the spread of diseases in crops (Gilbertson et al. 2015; Roditakis et al. 2017). In this context, bifenthrin, cartap, chlorfenapyr and chlorpyrifos insecticides are suitable products for use in integrated management programs of *B. tabaci* as they presented efficient (≥80%) and fast-acting (<24h) pest control. As the period of viral acquisition and transmission by *B. tabaci* is about 24 h, the use of the four insecticides selected in this study allows for the control of the pest before it effectively acquires or transmits viruses to the host plants (Gilbertson et al. 2015; Roditakis et al. 2017).

The fact that the four insecticides that caused high mortality (≥80%) in *B. tabaci* have a short residual period of control (up to three days) indicates that after this period, in the case of a new pest infestation, another insecticide application is required to generate efficient control. Therefore, adequate sampling frequency associated with knowledge of pest population levels when making control decisions should be taken into account to detect *B. tabaci* infestations and to use chemical control before the insect causes economic damage (Gusmão et al. 2006). It is also important that the control be applied in areas neighboring the crop to minimize the occurrence of migration of *B. tabaci* to the crop (Naranjo et al. 2009; Barro et al. 2011; Abdelkrim et al. 2017).

The insecticides efficient in controlling *B. tabaci* (bifenthrin, cartap, chlorfenapyr and chlorpyrifos) did not show physiological selectivity for the predator *O. tristicolor*. Therefore, these insecticides should be applied using principles of ecological selectivity such as applying the insecticide in places or times so as to minimize exposure of the predator to the insecticide (Ripper et al. 1951). Predatory pirate bugs have diurnal activity and their visitation to crops is greater during the warmest period of the day. Therefore, insecticide spraying for *B. tabaci* control should be realized at night or late afternoon (Ramos et al. 2017; Lattin 1999; Fernandes et al. 2010). To reduce the exposure of the predator to the insecticides, it is necessary that their applications be directed toward the plant locations where pest attacks occur, avoiding the occurrence of drift and minimizing exposure of the natural enemy with the insecticides. Insecticide spraying should be directed toward the plant apical and median canopies, given that these are the main attack sites of *B. tabaci* (Gusmão et al. 2006). Moreover, spraying pressure, water volume, type of spray-nozzle and equipment should also be selected to avoid exposure of the predator (Ripper et al. 1951; Garcerá et al. 2014; Bynum et al. 1991; Yu et al. 2009).

5. Conclusion

In the present study, we conducted an investigation where we found that from the 17 insecticides tested, only four (bifenthrin, cartap, chlorfenapyr and chlorpyrifos) caused mortality ≥ 80%. However, because of the short residual period of control for the pest and the absence of physiological selectivity for the predator, the use of these products requires a more

sustainable environmental approach. The consideration of pest population levels when making control decisions and the use of selectivity based on ecological principles to minimize predator exposure to the insecticides are pest management measures that positively contribute to more efficient sustainable whitefly IPM programs. In addition, strategies to improve biological control in agroecosystems, including cultural control strategies to make the agricultural environment more favorable to predators, such as providing alternative food and shelter sources are strategies that must be implemented to make whitefly management more sustainable.

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