

# Toxicity of insecticides to the sweetpotato whitefly (Hemiptera: Aleyrodidae) and its natural enemies

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**Abstract:** Efficient chemical control is achieved when insecticides are active against insect pests and safe to natural enemies. In this study, the toxicity of 17 insecticides to the sweetpotato whitefly, *Bemisia tabaci* (Gennadius), and the selectivity of seven insecticides to natural enemies of this insect pest were evaluated. To determine the insecticide toxicity, *B. tabaci* adults were exposed to abamectin, acephate, acetamiprid, cartap, imidacloprid, malathion, methamidophos, bifenthrin, cypermethrin, deltamethrin, esfenvalerate, fenitrothion, fenpropathrin, fenthion, phenthoate, permethrin and trichlorphon at 50 and 100% of the field rate (FR), and to water (untreated control). To determine the insecticide selectivity, adults of *Encarsia* sp., *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. were exposed to abamectin, acephate, acetamiprid, cartap, imidacloprid, malathion and methamidophos at 50 and 100% FR, and to water. Groups of each insect species were exposed to kale leaves preimmersed in each treatment under laboratory conditions. Mortality of exposed individuals was recorded 24 h after treatment. Cartap and imidacloprid at 50 and 100% FR and abamectin and acetamiprid at 100% FR showed insecticidal activity to *B. tabaci* adults. Abamectin at 50 and 100% FR was the least insecticidal compound to the natural enemies *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. The present results suggest that abamectin at 100% FR may decrease *B. tabaci* field populations but can still be harmless to predators. Implications of these results within an integrated pest management context are discussed.

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**Keywords:** *Brassica oleracea*; *Bemisia tabaci*; insecticide selectivity; conservation biological control

## 1 INTRODUCTION

The sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), comprises sibling species and/or biotypes that cause great economical damage to field and greenhouse crops worldwide, reaching up to 100% of losses<sup>1,2</sup> in subtropical and tropical regions.<sup>3</sup> *Bemisia tabaci* is also important within a social context for increasing levels of unemployment in some rural areas.<sup>1,2</sup>

Infestation by *B. tabaci* modifies the vegetative and reproductive development of the injured plant.<sup>4</sup> This insect can cause direct damage by sucking the plant sap and injecting toxins in the plant. The latter causes physiological changes including leaf silvering in cucurbits,<sup>5</sup> irregular ripening of tomatoes,<sup>6</sup> foliar disorders in ornamentals<sup>7</sup> and white streaking on *Brassica* species.<sup>8</sup> *Bemisia tabaci* also causes indirect damage by transmission of up to 17 different types of geminivirus<sup>9</sup> and excretion of honeydew. The growth of sooty mould on honeydew decreases photosynthesis and damages harvestable parts.<sup>10</sup>

Damage caused by insects is the major reason for crop failure in *Brassica* species.<sup>11</sup> Because *B. tabaci* often reaches economic injury levels in *Brassica* species, the management of this insect

frequently relies on insecticide sprays, which results in a high cost-benefit ratio and environmental contamination. Frequent insecticide applications are the most significant factor disrupting biological control of arthropod pests in cropping systems.<sup>12</sup> Moreover, characteristics of *B. tabaci* including polyphagy, high mobility (adults) and resistance to insecticides make outbreaks caused by insecticide disruption of biological control even more troublesome in areas where *Brassica* species and other *Bemisia* hosts are cultivated in a mosaic of crops.<sup>13</sup>

Conservation of natural enemies in integrated pest management (IPM) programmes is enhanced through habitat manipulation or use of selective insecticides.<sup>14</sup> By definition, selective insecticides are primarily harmful to insect pests but relatively harmless to natural enemies,<sup>15</sup> and their use may increase the effectiveness of biological control. Therefore, the use of selective insecticides enhances conservation of natural enemies and may reduce the likelihood of pest resurgence<sup>16</sup> and the number of insecticide applications.<sup>17</sup>

Natural enemies associated with *B. tabaci* infestations can cause high levels of mortality to populations of this insect pest. Among parasitoids, *Encarsia* is

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(Received 20 November 2006; revised version received 22 January 2007; accepted 16 February 2007)

Published online 23 May 2007; DOI: 10.1002/ps.1393

the most important genus, with 34 described species, and *E. formosa* (Gahan) (Hymenoptera: Aphelinidae) is the most abundant of these. Among predators, there are 114 species of arthropods distributed in nine orders and 31 families.<sup>18</sup> However, the identification of predators in field conditions is more difficult because many are generalists, and identification methods are sometimes inefficient.<sup>18,19</sup>

In Brazil there is a paucity of research to identify the main natural enemies of *B. tabaci*. Therefore, many predatory arthropods are not yet described, and may be potential agents of biological control of this insect pest. The group of non-described natural enemies include the predators *Discodon* sp. (Coleoptera: Cantharidae), *Acanthinus* sp., (Coleoptera: Anthicidae) and *Lasiochilus* sp. (Heteroptera: Anthocoridae) which are frequently associated with *Brassica* species infested with *B. tabaci* (Picanço MC, private communication).

Laboratory studies are useful for predicting the response of natural enemies to insecticide applications.<sup>19</sup> Although *B. tabaci* is an important insect pest, and its control may be achieved by the conservation of natural enemies, there is no study evaluating insecticide selectivity to natural enemies. Therefore, in this paper, the following were determined: (i) the toxicity of 17 commonly used insecticides in *Brassicaceae* to adults of *B. tabaci*; (ii) the selectivity of seven out of those 17 insecticides to natural enemies *Encarsia* sp., *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp.; and (iii) the tolerance of these natural enemies to insecticides used in *Brassicaceae*.

## 2 MATERIALS AND METHODS

### 2.1 Insects

*Bemisia tabaci* and *Encarsia* sp. adults were obtained from colonies maintained in greenhouses at the Universidade Federal de Viçosa (UFV), Viçosa, Minas Gerais, Brazil. Colonies were founded with adults and nymphs of *B. tabaci* collected in fields at the UFV experimental station, Viçosa, Minas Gerais. Adults of *B. tabaci* were collected using plastic containers and aspirators, and nymphs were obtained from infested plants. The adults were released in a 4 × 6 m greenhouse with 50 plants of cabbage, *Brassica oleracea capitata* L., that were free of insect and disease infestation. Cabbage seedlings were transplanted in 5 L plastic containers containing three-quarters of soil and one-quarter of livestock manure. When *B. tabaci* adults were released in the greenhouse, cabbage plants were 60 days old. Old plants were replaced with new ones every week. Nymphs of *B. tabaci* collected from the field were maintained in 50 × 50 × 50 cm cages for *Encarsia* sp. eclosion. The cages were made with organza in a wood frame. Newly emerged *Encarsia* sp. adults were released in another 4 × 6 m greenhouse with cabbage plants infested with *B. tabaci* adults. In addition, *Encarsia* sp. adults were fed with cotton balls containing 10% honey solution.<sup>20</sup>

Adults of *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. were collected directly from the field using plastic containers and aspirators. These species were collected in random plants from the same cabbage fields located at the UFV experimental station. Specimens of insect species were stored in 4 mL vials containing 70% alcohol and sent to taxonomists for identification.

### 2.2 Determination of toxicity of insecticides to *Bemisia tabaci*

The experiment was conducted as a randomized complete design and consisted of 34 factorial treatments (17 insecticides and two doses of each insecticide), four replications and 40–50 individuals per replication. Insecticide choice was made to cover the main products used in the control of *B. tabaci* in Brazil (Table 1).

Insecticides were tested in concentrations representing 50 and 100% of the field rate (FR) recommended for the control of *B. tabaci*. The use of 50% FR was utilized to observe the insecticide impact on natural enemies when these break down to half of their original concentration.<sup>21</sup> A non-ionic surfactant polyoxyethylene alkyl phenyl ether at 0.03 g L<sup>-1</sup> was included in all treatments.<sup>22</sup> Leaves dipped in water and surfactant were used as control to estimate natural mortality.

In this study, the leaf dipping method was used so as to provide uniform treated area on the leaf surface. Kale leaf discs (90 mm in diameter) were immersed in insecticide solution for 5 s. Treated leaves were dried at room temperature for 2 h and then placed on the bottom of clean plastic petri dishes (90 mm × 20 mm). The petri dishes with treated leaves were covered with organza and tied with rubber bands. In each petri dish, 40–50 *B. tabaci* adults were released using aspirators; this constituted the experimental unit. The petri dishes were maintained at 25 ± 0.5 °C and a relative humidity of 75 ± 5%. Mortality of *B. tabaci* adults was recorded 24 h after treatment, with mortality defined as immobility of the insects on stimulation with a fine camel-hair brush. To evaluate mortality, petri dishes with treated leaves and insects were opened inside plastic bags to prevent individuals flying away.

### 2.3 Determination of toxicity of insecticides to *Encarsia* sp., *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp.

The experiment was conducted as a randomized complete design and consisted of 56 factorial treatments (seven insecticides, two doses of each insecticide, and four natural enemies) and four replications. Out of the 17 insecticides used in the bioassay with *B. tabaci*, abamectin, acetamiprid, cartap, imidacloprid, acephate, malathion and methamidophos were selected for evaluation of toxicity on *Encarsia* sp., *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. Insecticides were tested on the same doses (50 and 100% FR) as those used on the bioassay with *B. tabaci*. Because the number of insects collected

**Table 1.** Insecticides used in bioassays to evaluate toxicity to *Bemisia tabaci*, *Encarsia* sp., *Discodon* sp., *Acanthinus* sp. and *Lasiochilus* sp

Insecticide, formulation	Commercial name	Class	Manufacturer	Rate (g Al ha <sup>-1</sup> ) <sup>a</sup>	
				100% FR	50% FR
Abamectin 18 g L <sup>-1</sup> EC <sup>b</sup>	Vertimec 18 CE	Avermectin	Syngenta Proteção de Cultivos	10.8	5.4
Acephate 750 g kg <sup>-1</sup> SP <sup>b</sup>	Orthene 750 BR	Organophosphate	Arysta Lifescience do Brasil	630	315
Acetamiprid 200 g kg <sup>-1</sup> SP <sup>b</sup>	Mospilan	Neonicotinoid	Iharabras SA	48	24
Bifenthrin 25 g L <sup>-1</sup> EC	Brigate 25 CE	Pyrethroid	FMC Química do Brasil	4.8	2.4
Cartap 500 g kg <sup>-1</sup> SP <sup>b</sup>	Thiobel 500	Nereistoxin	Arysta Lifescience do Brasil	750	375
Cypermethrin 200 g L <sup>-1</sup> EC	Arrivo 200 CE	Pyrethroid	FMC Química do Brasil	72	36
Deltamethrin 25 g L <sup>-1</sup> EC	Decis 25 CE	Pyrethroid	Bayer Cropscience	7.2	3.6
Esfenvalerate 25 g L <sup>-1</sup> EC	Sumidan 25 CE	Pyrethroid	Sumitomo Chemical do Brasil	11.4	5.7
Fenitrothion 500 g L <sup>-1</sup> EC	Sumithion 500 CE	Organophosphate	Sumitomo Chemical do Brasil	600	300
Fenpropathrin 300 g L <sup>-1</sup> EC	Danimem 300 CE	Pyrethroid	Sumitomo Chemical do Brasil	117	58.5
Fenthion 500 g L <sup>-1</sup> EC	Lebaycid 500	Organophosphate	Bayer Cropscience	300	150
Phenthoate 500 g L <sup>-1</sup> EC	Elsan	Organophosphate	Mitsubishi Corporation do Brasil	660	330
Imidacloprid 700 g kg <sup>-1</sup> WG <sup>b</sup>	Confidor 700 WG	Neonicotinoid	Bayer Cropscience	450	225
Malathion 500 g L <sup>-1</sup> EC <sup>b</sup>	Malathion 500 CE Sultox	Organophosphate	Action SA	4500	2250
Methamidophos 600 g L <sup>-1</sup> EC <sup>b</sup>	Tamaron BR	Organophosphate	Bayer Cropscience	1080	540
Permethrin 500 g L <sup>-1</sup> EC	Ambush 500 CE	Pyrethroid	Syngenta Proteção de Cultivos	60	30
Trichlorphon 500 g L <sup>-1</sup> SL	Dipterex 500	Organophosphate	Bayer Cropscience	900	450

<sup>a</sup> 50 and 100% of field rate (FR) for a sprayer delivering 600 L ha<sup>-1</sup> (392 gal acre<sup>-1</sup>).

<sup>b</sup> Insecticides used in the bioassays with the natural enemies *Encarsia* sp., *Discodon* sp., *Acanthinus* sp. and *Lasiochilus* sp.

in the field was limited, bioassays with the insecticides abamectin, acetamiprid, cartap and imidacloprid, which were effective against *B. tabaci*, were prioritized. Provided that natural enemies were available, some pesticides that were ineffective against *B. tabaci* were also tested, among them acephate, malathion and methamidophos. As in the bioassays with *B. tabaci*, non-ionic surfactant polyoxyethylene alkyl phenyl ether at 0.03 g L<sup>-1</sup> was used in all treatments.<sup>22</sup> Leaves dipped in water and surfactant were used as control to estimate natural mortality.

The insecticide exposure technique used in bioassays with natural enemies was the same as that described in Section 2.2 for bioassays with *B. tabaci*. The experimental units were 50–60 adults of *Encarsia* sp., 20–25 adults of *Acanthinus* sp., 20–25 adults of *Lasiochilus* sp. and 10–15 adults of *Discodon* sp. In each experimental unit, an *ad libitum* supply of diet made from 10% honey in water was provided to the natural enemies. The petri dishes were maintained at 25 ± 0.5 °C and a relative humidity of 75 ± 5%. Mortality of treated insects was recorded 24 h after treatment, with mortality defined as immobility of the insects on stimulation with a fine camel-hair brush. To evaluate mortality, petri dishes with treated leaves and insects were opened inside plastic bags to prevent live individuals flying away.

## 2.4 Data analysis

In all experiments, mortality was adjusted to the insect survival on untreated leaves using Abbott's formula.<sup>23</sup> Mean percentage mortalities of adults of *B. tabaci*, *Encarsia* sp., *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. were transformed by arcsine square root and subjected to analysis of variance (ANOVA).<sup>24</sup>

Significant means were separated by a Scott–Knott test ( $P < 0.05$ ).<sup>25</sup>

The criterion for evaluating the efficiency of insecticides to *B. tabaci* was based on the threshold of 80% mortality. This criterion of efficiency is required by the Brazilian Ministry of Agriculture for the registration of an insecticide for agricultural use in Brazil. Therefore, an insecticide was considered efficient (i.e. insecticidal) if it caused mortality equal to or greater than 80%. For natural enemies, insecticides were grouped as highly insecticidal (mortality greater than 75%), insecticidal (mortality between 50 and 75%) and slightly insecticidal (mortality between 25 and 50%). Selectivity of an insecticide was based on the proportional mortality of the insect pest compared with its natural enemy after the insecticide treatment. An insecticide was considered selective when mortality of the insect pest was higher than that of its natural enemy. On the other hand, an insecticide was considered non-selective when mortality of the insect pest was similar to that of its natural enemy. Finally, an insecticide was considered harmful when mortality of the insect pest was lower than that of its natural enemy.<sup>26</sup>

## 3 RESULTS

### 3.1 Toxicity of insecticides to *Bemisia tabaci*

There were statistically significant differences in the mortalities of *B. tabaci* caused by insecticides ( $F = 145.53$ ;  $df = 16, 102$ ;  $P < 0.001$ ), doses ( $F = 63.76$ ;  $df = 1, 102$ ;  $P < 0.001$ ) and the two-way interaction (insecticides × doses) ( $F = 5.72$ ;  $df = 16, 102$ ;  $P < 0.001$ ).

Cartap and imidacloprid at 50 and 100% FR and abamectin and acetamiprid at 100% FR were efficient

**Table 2.** Toxicity of insecticides to *Bemisia tabaci* at 50 and 100% of field rate (FR)

Insecticide	Mortality (%) <sup>a</sup>	
	100% FR	50% FR
Cartap	100 aA	99 aA
Abamectin	89 aA	57 bC
Imidacloprid	81 aB	78 aB
Acetamiprid	76 aB	41 bD
Bifenthrin	31 aC	10 bF
Malathion	29 aC	10 bF
Fenpropathrin	27 aC	18 aE
Methamidophos	19 aD	0.2 bF
Deltamethrin	18 aD	18 aE
Fenthion	17 aD	5 bF
Cypermethrin	15 aD	11 aF
Phenthoate	13 aD	23 aE
Permethrin	13 aD	6 aF
Esfenvalerate	11 aD	2 aF
Acephate	6 aE	3 aF
Fenitrothion	5 aE	6 aF
Trichlorphon	4 aE	0.7 aF

<sup>a</sup> Means followed by the same lower-case letter (within rows) and upper-case letter (within columns) are not significantly different by the Scott–Knott test ( $P < 0.05$ ).

in controlling *B. tabaci*, with mortalities equal to or greater than 80% (Table 2). The high mortality of *B. tabaci* caused by abamectin and acetamiprid at 100% FR decreased when these insecticides were applied at 50% FR (Table 2). The organophosphate insecticides acephate, fenitrothion, fenthion, phenthoate, malathion, methamidophos and trichlorfon and the pyrethroids bifenthrin, cypermethrin, deltamethrin, esfenvalerate, fenpropathrin and permethrin were inefficient in controlling *B. tabaci*. The mortalities caused by these pesticides were lower than 80% even at 100% FR (Table 2). The low mortality of *B. tabaci* caused by bifenthrin, malathion, methamidophos or fenthion at 100% FR decreased when these insecticides were applied at 50% FR (Table 2).

### 3.2 Toxicity of insecticides to *Encarsia* sp., *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp

There were statistically significant differences in the mortalities of *Encarsia* sp., *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. caused by insecticides ( $F = 36.06$ ;  $df = 6, 210$ ;  $P < 0.001$ ) and doses ( $F = 5.28$ ;  $df = 1, 28$ ;  $P = 0.023$ ). The two-way interaction (insecticides  $\times$  doses) was not statistically significant ( $F = 0.62$ ;  $df = 6, 210$ ;  $P > 0.5$ ).

The insecticides cartap, imidacloprid, malathion, methamidophos, acephate, acetamiprid and abamectin at 50 and 100% FR were highly insecticidal (mortalities greater than 61%) to *Encarsia* sp. (Table 3).

The insecticides cartap, imidacloprid, malathion, methamidophos and acephate at 50 and 100% FR were highly insecticidal (mortalities greater than 90%) to *Acanthinus* sp. Acetamiprid was highly insecticidal (89% mortality) at 100% FR and insecticidal (32%

**Table 3.** Toxicity of insecticides at 50 and 100% of field rate (FR) to adults of *Acanthinus* sp., *Discodon* sp., *Lasiochilus* sp. and *Encarsia* sp

Insecticide	Mortality (%) <sup>a</sup>	
	100% FR	50% FR
<i>Acanthinus</i> sp.		
Cartap	100 aA	100 aA
Abamectin	0 aB	0 aB
Imidacloprid	100 aA	100 aA
Acetamiprid	90 aA	32 bB
Malathion	100 aA	97 aA
Methamidophos	100 aA	100 aA
Acephate	100 aA	97 aA
<i>Discodon</i> sp.		
Cartap	100 aA	100 aA
Abamectin	12 aB	4 aB
Imidacloprid	100 aA	84 aA
Acetamiprid	46 aB	31 aB
Malathion	78 aA	78 aA
Methamidophos	100 aA	100 aA
Acephate	75 aA	44 bB
<i>Lasiochilus</i> sp.		
Cartap	77 aA	57 aB
Abamectin	11 aB	4 aC
Imidacloprid	100 aA	83 aA
Acetamiprid	62 aA	64 aB
Malathion	100 aA	100 aA
Methamidophos	100 aA	100 aA
Acephate	93 aA	90 aA
<i>Encarsia</i> sp.		
Cartap	100 aA	100 aA
Abamectin	97 aA	86 aA
Imidacloprid	72 aA	62 aA
Acetamiprid	95 aA	86 aA
Malathion	100 aA	100 aA
Methamidophos	100 aA	100 aA
Acephate	100 aA	100 aA

<sup>a</sup> Means followed by the same lower-case letter (within rows) and upper-case letter (within columns) are not significantly different by the Scott–Knott test ( $P < 0.05$ ).

mortality) at 50% FR. Abamectin at 50 and 100% FR was not insecticidal to *Acanthinus* sp. adults (Table 3).

The insecticides cartap, imidacloprid, malathion and methamidophos at 50 and 100% FR were highly insecticidal (mortalities between 78 and 100%) to *Discodon* sp. Acephate was highly insecticidal (75% mortality) at 100% FR and insecticidal (43% mortality) at 50% FR. Acetamiprid at 50 and 100% FR was insecticidal (46 and 31% mortality respectively). Abamectin at 50 and 100% FR was not insecticidal to *Discodon* sp. adults (Table 3).

The insecticides imidacloprid, malathion, methamidophos and acephate at 50 and 100% FR were highly insecticidal (mortalities greater than 80%) to *Lasiochilus* sp. Cartap and acetamiprid were insecticidal (57 and 76% mortality and 63 and 61% mortality respectively) at 50 and 100% FR. Abamectin at 50 and 100% FR was not insecticidal to *Lasiochilus* sp. adults (Table 3).

**Table 4.** Selectivity of insecticides and tolerance of natural enemies *Acanthinus* sp., *Discodon* sp., *Lasiochilus* sp. and *Encarsia* sp. to insecticides at 50 and 100% field rate (FR) commonly used to control *Bemisia tabaci*

Insecticide	Pest			Natural enemy					
	<i>B. tabaci</i>	<i>Acanthinus</i> sp.		<i>Discodon</i> sp.		<i>Lasiochilus</i> sp.		<i>Encarsia</i> sp.	
	Mortality <sup>a</sup>	Mortality <sup>a</sup>	LS <sup>b</sup>	Mortality <sup>a</sup>	LS <sup>b</sup>	Mortality <sup>a</sup>	LS <sup>b</sup>	Mortality <sup>a</sup>	LS <sup>b</sup>
100% FR									
Cartap	100 a	100 aA	1.00	100 aA	1.00	77 aA	1.31	100 aA	1.00
Abamectin	90 a	0 bB	High	12 bB	7.34	11 bB	8.00	97 aA	0.93
Imidacloprid	81 a	100 aA	0.81	100 aA	0.81	100 aA	0.81	72 aA	1.13
Acetamiprid	76 a	90 aA	0.85	46 aA	1.66	62 aA	1.23	95 aA	0.80
Malathion	29 b	100 aA	0.29	78 aA	0.37	100 aA	0.29	100 aA	0.29
Methamidophos	19 b	100 aA	0.19	100 aA	0.19	100 aA	0.19	100 aA	0.19
Acephate	6 b	100 aA	0.06	75 aA	0.08	93 aA	0.07	100 aA	0.06
50% FR									
Cartap	99 a	100 aA	1.00	100 aA	1.00	57 aA	1.74	100 aA	1.00
Abamectin	57 a	0 bB	High	4 bB	12.7	4 bB	15.1	86 aA	0.66
Imidacloprid	78 a	100 aA	0.78	84 aA	0.93	83 aA	0.94	62 aA	1.27
Acetamiprid	41 a	32 aB	1.27	31 aB	1.32	64 aA	0.65	86 aA	0.48
Malathion	10 b	97 aA	0.11	78 aA	0.13	100 aA	0.10	100 aA	0.10
Methamidophos	0.2 b	100 aA	0.00	100 aA	0.00	100 aA	0.00	100 aA	0.00
Acephate	2 b	97 aA	0.03	44 bB	0.06	90 aA	0.03	100 aA	0.03

<sup>a</sup> Values represent the mean percent mortality. Means followed by the same lower-case letter (within rows for comparison of insecticide selectivity) and upper-case letter (within rows for comparison of insecticide tolerance among natural enemies) are not significantly different by the Scott-Knott test ( $P < 0.05$ )

<sup>b</sup> Level of selectivity [mortality (%) of *B. tabaci*/mortality (%) of natural enemy].

### 3.3 Tolerance of *Encarsia* sp., *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. to insecticides

Insecticide tolerance varied according to the species of natural enemy ( $F = 5.71$ ;  $df = 3, 216$ ;  $P = 0.001$ ) and the dose of the insecticide ( $F = 2.86$ ;  $df = 1, 216$ ;  $P = 0.092$ ). The two-way interaction (natural enemy species  $\times$  dose) was not statistically significant ( $F = 0.09$ ;  $df = 3, 216$ ;  $P > 0.5$ ).

The predators *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. were more tolerant to abamectin at 50 and 100% FR than *Encarsia* sp. *Acanthinus* sp. and *Discodon* sp. were more tolerant to acetamiprid at 50% FR than *Lasiochilus* sp. and *Encarsia* sp. *Discodon* sp. was more tolerant to acephate at 50 and 100% FR than *Acanthinus* sp., *Lasiochilus* sp. and *Encarsia* sp. (Table 4).

### 3.4 Selectivity of insecticides to *Encarsia* sp., *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. compared with *Bemisia tabaci*

There were statistically significant differences in mortality of *B. tabaci*, *Encarsia* sp., *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. as a function of species ( $F = 12.58$ ;  $df = 4, 270$ ;  $P < 0.001$ ) and dose ( $F = 5.11$ ;  $df = 1, 270$ ;  $P = 0.024$ ). The two-way interaction (species  $\times$  dose) was not statistically significant ( $F = 0.24$ ;  $df = 4, 270$ ;  $P > 0.05$ ).

Abamectin was selective (i.e. caused greater mortality to *B. tabaci* than to the treated predators) for *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. at 50 and 100% FR. Cartap, imidacloprid and acetamiprid were not selective (i.e. caused similar mortalities to *B. tabaci* and natural enemies) to *Acanthinus* sp., *Discodon*

sp. and *Lasiochilus* sp. at 50 and 100% FR. In addition, abamectin was not selective to *Encarsia* sp. at 50 and 100% FR, and acephate was not selective to *Discodon* sp. at 50% FR. Malathion and methamidophos at 50 and 100% FR and acephate at 100% FR were harmful (i.e. caused less mortality to *B. tabaci* than to its natural enemies) to *Encarsia* sp., *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. Similarly, acephate at 50% FR was harmful to *Acanthinus* sp., *Lasiochilus* sp. and *Encarsia* sp. (Table 4).

## 4 DISCUSSION

Non-conventional insecticides such as cartap, avermectin and neonicotinoids were more efficient in controlling *B. tabaci* than the conventional insecticides (i.e. organophosphates and pyrethroids). These results corroborate those of previous studies<sup>27–29</sup> which showed the high efficiency of cartap (nereistoxin), abamectin (avermectin) and imidacloprid (neonicotinoid) in controlling *B. tabaci*. Seed treatment with imidacloprid followed by four foliar sprays (one spray per week) had efficiencies of 83, 92 and 70% in controlling eggs, nymphs and adults of *B. tabaci* respectively.<sup>30</sup> Acetamiprid has shown greater efficiency than imidacloprid when used as a foliar spray. The higher efficiency of acetamiprid may be the consequence of its greater solubility in water ( $4.25 \text{ g L}^{-1}$  at  $25^\circ\text{C}$ ) which enhances diffusion in the leaf tissue.<sup>31</sup>

Mortalities caused by cartap and imidacloprid were high even when these insecticides were applied at 50% FR. Therefore, their high efficiency will continue after breakdown of up to half of their active ingredient.

However, the mortalities caused by abamectin and acetamiprid were reduced when these insecticides were applied at 50% FR. Consequently, these insecticides have reduced effects when their active ingredients break down to half quantity. These results could have practical implications for the management of *B. tabaci* populations, indicating that delivery of the recommended field rate is essential to achieve acceptable population reduction.

The conventional organophosphate and pyrethroid insecticides were not efficient in controlling *B. tabaci*. Similar results have been reported for *B. tabaci* in the literature,<sup>28</sup> which could be explained by the development of resistant populations. Behavioural and biological characteristics of *B. tabaci*, such as short development time, high fecundity and great capacity for dispersion, in addition to the high frequency of use of these insecticides, have contributed to the development of *B. tabaci* resistance to such conventional insecticides.<sup>13,32,33</sup> In contrast, Prabhaker *et al.*<sup>32</sup> showed that greater mortality of *B. tabaci* can be achieved by combining high concentrations of pyrethroids with regular concentrations of organophosphates. The greater efficiency of this mixture compared with the use of the individual insecticides can be the result of the added toxicity caused by the blocking of sodium channels by the pyrethroids and the inhibition of acetylcholinesterase by the organophosphates. In addition to this synergistic effect, the greater toxicity could be result of the inhibition of *B. tabaci* resistance mechanisms against these insecticides.<sup>33</sup> However, the use of conventional pesticides to synergize pyrethroids has failed to control whiteflies in cotton.<sup>34</sup>

The tolerance of *B. tabaci* to organophosphate and pyrethroids could be related to the lower rate of insecticide penetration through the insect integument,<sup>35</sup> the high rate of insecticide breakdown and/or the insensitivity of the target site of these insecticides.<sup>15</sup> The rate of penetration of an insecticide into the insect integument is associated with its physicochemical properties and with the thickness and chemical composition of the insect cuticle. Therefore, since affinity for lipids is inversely proportional to the solubility of the insecticide in water, lipophilic insecticides penetrate the insect body at higher rates owing to the chemical characteristics of the insect cuticle.<sup>36</sup>

The presence of monooxygenases with affinity for organophosphates may be associated with the tolerance of *B. tabaci* to this class of insecticides. These detoxification enzyme systems transform lipophilic insecticides into polar metabolites that are then excreted.<sup>37</sup> This hypothesis is based on the high lipophilic character of these insecticides,<sup>38</sup> as well on P450-dependent monooxygenases being the main enzymes involved in the metabolism of organophosphates in insects.<sup>35</sup> Moreover, modifications in the enzyme acetylcholinesterase present in *B. tabaci* and the high velocity with which this enzyme metabolizes

the neurotransmitter acetylcholine may be responsible for the tolerance of *B. tabaci* to organophosphates.<sup>39</sup>

Similarly, the metabolism of pyrethroids by microsomal oxidases and esterases may result in greater detoxification of these insecticides in the insect body.<sup>15</sup> Modifications in the sodium channels that change the sensitivity of the enzymes (Na-K)-ATPase and Mg<sub>2</sub>-ATPase may also be responsible for the reduction in neuroinsecticidal action of pyrethroids.<sup>40,41</sup>

The high toxicity of the organophosphates malathion, methamidophos and acephate to natural enemies is possibly associated with the low molecular masses of these molecules (330.4, 141.1 and 183.2 respectively).<sup>38</sup> According to Stock and Holloway,<sup>42</sup> substances with low molecular mass have higher capacity for penetration into the insect cuticle. The low toxicity of abamectin, which is the combination of two avermectins (B1a and B1b), could be the consequence of their high molecular masses (873.1 and 859.1 respectively).<sup>38</sup> Comparing the two neonicotinoids, acetamiprid was less insecticidal to natural enemies than imidacloprid, possibly owing to the lower affinity of acetamiprid for the lipophilic cuticle of insects. Acetamiprid and imidacloprid have low molecular masses (255.7 and 22.7 respectively) and low affinity for the lipophilic cuticle of insects. However, acetamiprid has greater solubility in water (2.95 g L<sup>-1</sup> at 25 °C) than imidacloprid (0.51 g L<sup>-1</sup> at 20 °C).<sup>38</sup>

Predators were more tolerant to insecticides than the parasitoid *Encarsia* sp. These results could be related to the greater body size of predators compared with that of the parasitoid *Encarsia* sp. As the body size increases, the specific area decreases, and consequently there is less exposure to insecticides.<sup>43</sup> Mechanisms of tolerance to insecticides in natural enemies may be the same as those involved with insecticide resistance in insect pests. Therefore, the selectivity of abamectin in favour of predators may be related to differences in insecticide penetration, target site and/or action of detoxification enzymes in predators.<sup>44</sup> Leite *et al.*<sup>36</sup> showed that abamectin was selective to the predatory wasp *Brachygastra lecheguana* (Latreille) (Hymenoptera: Vespidae) of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in tomato.

In the present study, cartap, abamectin, imidacloprid and acetamiprid were efficient in controlling *B. tabaci*, and abamectin was selective to *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. In contrast, the organophosphates and pyrethroids tested were not insecticidal to *B. tabaci* and were not selective to natural enemies. Although cartap, imidacloprid and acetamiprid were efficient against *B. tabaci*, they were not selective to the natural enemies tested. Therefore, to obtain better results in integrating insecticide use and biological control, abamectin may be preferred over the organophosphates, pyrethroids, neonicotinoids and nereistoxins when *Acanthinus* sp., *Discodon* sp. and *Lasiochilus* sp. are the most abundant natural enemies in the field. The lack of insecticidal activity in

organophosphates and pyrethroids suggests that their use to manage *B. tabaci* should not be recommended for the area where this study was conducted.

It is important to note that the behavioural and biological characteristics of *B. tabaci*, including short development time and high fecundity, polyphagy and mobility,<sup>13,33,34</sup> may cause rapid changes in tolerance to pesticides in different agroecosystems over the years. Therefore, the levels of insecticidal activity and selectivity obtained here are not static and can change in space and time. Because insects from a single site and time point were used, we cannot predict what may happen in other areas or within the same area during years to come. The present results should be considered within a life-system perspective where components of the agroecosystem and management practices for *B. tabaci* populations will determine the abundance and composition of whitefly biotypes, which may consequently affect the relationship between responses of whiteflies and their natural enemies.

Finally, although laboratory studies are useful for predicting the response of natural enemies to insecticide applications,<sup>19</sup> field studies are necessary to compare the suppression of *B. tabaci* and the abundance of beneficial insects under field exposure conditions. Laboratory studies use a uniform deposit structure and disregard insect behaviour, which can change the dose transfer process and ultimately affect toxicity.<sup>45</sup> In spite of this simplification, the present study is appropriate to understand the relative impact of the insecticides tested because the toxicities to *B. tabaci* and natural enemies were compared using the same conditions. The availability of selective insecticides to manage key pests such as *B. tabaci* is critical for the development of sound IPM programmes. Future studies should test additional insecticides that are currently used to manage *B. tabaci* for their efficiency and selectivity.

## ACKNOWLEDGEMENTS

The authors thank Dr Paulo Sérgio Fiuza Ferreira for the identification of *Lasiochilus* sp., Dr Ayr de Moura Bello for the identification of *Discodon* sp. and *Acanthinus* sp. and Dr Angélica M Penteadó Dias for the identification of *Encarsia* sp. This research was funded by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

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