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Managing Whitefly on Soybean

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Abstract

The whitefly *Bemisia tabaci* (Gennadius, 1889) is a major pest species in soybean, leading to severe economic losses on this crop due to the difficulties involved on its management. Previously restricted to the Middle-west and Southeast regions of Brazil, whitefly infestations have steadily increased in the Southern state of Rio Grande do Sul, the third biggest soybean growing region of the country. Control failures and scarcity of updated information have led Brazilian soybean growers to raise excessively the number of sprays per crop season, increasing control costs and jeopardizing the long-term sustainbility of this strategy due to selection of resistant strains and potential harmful effects on the environment. The aim of this work was to evaluate the performance of different chemical insecticides in the control of *B. tabaci* nymphs and adults on soybean crops in two different sites, under the field conditions faced by the growers in the state of Rio Grande do Sul. The most efficient treatment for the control of *B. tabaci* adults was cyantraniliprole + lambda-cyhalothrin, at the doses of 100 + 7.5 g a.i. ha^{-1}, which provided 65% of average control efficiency. As for nymph control, the most efficient treatment was acetamiprid + pyriproxyfen, at the doses of 60 + 30 g a.i. ha^{-1}, which resulted in 67% of whitefly control in average. Two sequential sprays beginning at the infestation onset are recommended in order to enhance control efficiency.

Keywords: *Bemisia tabaci*, chemical control, *Glycine max*, integrated pest management

1. Introduction

Soybean (*Glycine max*) is the main oil-seed crop grown and consumed in the world, with a worldwide production of 336.699 million tons in the 2017/18 cropping season (EMBRAPA, 2018), 35% of which were grown in Brazil (CONAB, 2018). Alongside Argentina, Paraguay and Bolivia, the total area grown with soybean in South America mounts up to 50 million hectares (FAOSTAT, 2018), most of which are severely attacked by the whitefly *Bemisia tabaci* (Gennadius, 1889) (Hemiptera: Aleyrodidae). While most pest species are associated with certain growth stages of the soybean plants (*e.g.*, *Sternechus subsignatus* in the beginning of the cycle, *Euchistus heros* and other stink bugs during the reproductive phase; see Hoffmann-Cmapo, Silva, & Oliveira, 1999, and Corrêa-Ferreira & Panizzi, 1999, respectively), favorable geographic and climatic conditions (*e.g.*, low air humidity and high mean temperatures; Sharma et al., 2013) can allow the occurrence of *B. tabaci* throughout the whole growing cycle of the soybean crop (as reported in Bolivia and the Middle-west region of Brazil), greatly increasing its damage potential and difficulting its control (Lima, Lara, & Barbosa, 2002).

Soybean plants are directly damaged by whiteflies due to sap sucking and toxin injection, and indirectly by virus transmission and excretion of honeydew, which serves as a substrate for the growth of sooty mold fungi (Hirose et al., 2015). Additionally, *B. tabaci* has been confirmed as a vector for about ten percent of all known plant pathogenic viruses (Fauquet et al., 2008), and the yield losses resulted from direct and indirect damages on soybean plants can reach up to 300 kg hectare^{-1} (APROSOJA, 2017). Short life cycle (16-25 days; Sottoriva, 2010) and high oviposition rates (160 eggs per female; Malumphy, Eyre & Anderson, 2017) allow *B. tabaci* to complete 11 to 15 generations per year, with the fast-increasing populations reaching its peak during the flowering stage of the soybean plants (Marabi et al., 2017). Control measures are often compromised due to the immobility of whitefly nymphs (Byrne & Bellows Jr., 1991) and its concentration in the middle and lower thirds of the plant canopy and bottom parts of the leaflets (Pozebon et al., 2019), thus avoinding direct contact with insecticide sprays.

The increasing occurrence of *B. tabaci* on Brazilian soybean fields may be associated with the abusive use of non-selective insecticides and its harmful effects on natural enemies (Vieira et al., 2012), as well as selection pressure on resistant strains of the pest (Silva, Omoto, Bleicher, & Dourado, 2009). Management programs of whitefly rely heavily on the use of chemical insecticides, due to the absence of alternatives such as biological control agents (*e.g.*, predators and parasitoids) and varietal resistance. Entomopathogenic fungi (*e.g.*, *Beauveria bassiana*) have been efficiently used in the control of whitefly nymphs (Neto & Barros, 2016), but the particularities involved in its use allied to the high number of fungicide sprays (usually four to five per crop cycle) prevent a broader adoption of such strategies. As a result, Brazilian soybean growers have reported the use of five to six insecticide sprays aiming specifically at this pest during the crop cycle (APROSOJA, 2017), with the total cost of whitefly control mounting up to U$ 75.00 hectare^{-1} (EMBRAPA, 2017).

Most researches on *B. tabaci* control are carried out in the Middle-west (Silva et al., 2003; Garcia et al., 2005; Silva et al., 2012) and Southeast (Alves et al., 2001; Valle, Lourenção, & Novo, 2002; Bacci et al., 2007) regions of Brazil, whereas whitefly infestations have been steadily increasing in the Southern states (Bernardi, 2016) and demanding up to 67% of all chemical insecticides sprayed on horticulture crops (Rosa, 2017). Satisfactory control efficiencies (≥ 80%) of *B. tabaci* are obtained only with highly specific and costly active ingredients, such as spiromesifene in cotton crops (Netto & Barros, 2016) and cyantraniliprole + lambda-cyhalothrin in tomato crops (Arnemann et al., 2019). In addition, while some sampling methods have been proposed (Czepak et al., 2018), a standardized method for monitoring and control decision remains absent due to the lack of a defined *economic injury level* for *B. tabaci* on soybean crops. In this sense, scientific research that supports the definition of efficient whitefly management strategies and ensures that this information is taken to the soybean growers and field professionals in Southern Brazil becomes extremely necessary.

The aim of this work was to evaluate the efficiency of chemical inseticides in the control of *B. tabaci* adults and nymphs on soybean plants under field conditions, in two different sites, in order to estabilish the most efficient strategy for whitefly control on soybean.

2. Materials and Methods

2.1 Experimental Sites

The experiments were set in Santa Cruz do Sul, Rio Grande do Sul, Brazil. The climate is classified as Cfa according to Köppen's classification (Köppen, 1948), which is defined as a humid subtropical climate with hot summers. The average temperature is 19.7 °C, with an annual rainfall of 1311 mm. Two areas were chosen as experimental sites in two different commercial soybean fields, where infestation of *B. tabaci* occurred naturally. The sowing date on Experiment I (29º49′17″ S, 52º22′44″ W, 122 meters a.s.l.) was 30/10/2017, with the experiment starting in 15/02/2018, when the soybean plants reached growth stage R1 (beginning of the reproductive stage). Whitefly infestation on Experiment I by the time of the first spraying was at a high level (9.68 adults leaflet^{-1} and 1.2 nymphs leaflet^{-1}, on average). Sowing on Experiment II (29°43′04″ S, 52°25′33″ W, 122 meters a.s.l.) was carried out in 15/01/2018, with the experiment starting in 14/03/2018, when the soybean plants reached growth stage R1. Infestation level on Experiment II at the moment of the first spraying was moderate to low, with 0.85 adults leaflet^{-1} and 0.7 nymphs leaflet^{-1}, on average.

2.2 Treatments

The choice of treatments was based on the insecticides commonly used by growers and recommended by field technicians in the region to control *B. tabaci* on soybean fields. The chemical insecticides composing the treatments, their respective active ingredients, modes of action in the insect's body and spray doses are shown on Table 1.

Table 1. Active ingredient, mode of action, spray dose and cost hectare^{-1} of the chemical insecticides evaluated for the control of *Bemisia tabaci* on soybean plants under field conditions. Santa Cruz do Sul, RS, Brazil. 2017/18 cropping season

Treatment	**Active ingredient**	**Mode of action**	**Dose ha^{-1}**		**Cost ha^{-1} (USD)**
			c.p.[1]	**a.i.**[2]	
T1	Acetamiprid + pyriproxyfen	Nicotinic acetylcholine receptor agonists + Juvenile hormone mimics	300	60+30	30.93
T2	Spiromesifene	Inhibitors of acetyl CoA carboxylase	600	144	22.42
T3	Cyantraniliprole	Ryanodine receptor modulators	1000	100	90.21
T4	Cyantraniliprole + lambda-cyhalothrin	Ryanodine receptor modulators + Sodium channel modulators	1000+30	100+7.5	31.06
T5	Pymetrozine	Chordotonal organ TRPV channel modulators	400	200	46.39
T6	Imidacloprid + lambda-cyhalothrin	Nicotinic acetylcholine receptor agonists + Sodium channel modulators	300+30	105+7.5	9.39
T7	Acetamiprid + bifenthrin	Nicotinic acetylcholine receptor agonists + Sodium channel modulators	160	40+40	12.37
T8	Cyantraniliprole + abamectin	Ryanodine receptor modulators + Glutamate-gated chloride channel (GluCl) allosteric modulators	750	45+13.5	48.97
T9	Untreated control	-	-	-	-

Note. [1] c.p. = Commercial product (g or mL hectare^{-1}); [2] a.i. = Active ingredient (g hectare^{-1}).

2.3 Experimental Design

The experiments were comprised of plots of 24 m² (4 m × 6 m), with 4 replicates per treatment, in a randomized block design. Sprayings were carried out using a CO_2-pressurized backpack sprayer, nozzles model TJ XR-11002VS, and 150 L ha^{-1} of spray volume. Both experiments received two sprays, with an interval of 7 days between them.

2.4 Evaluations

Evaluations were made at 0, 5 and 10 days after the first spraying (DA1S), and at 0, 5, 10, 15 and 20 days after the second spraying (DA2S). In each plot, 10 central leaflets were selected from random soybean plants, in the middle and upper thirds. In the abaxial side of these leaflets, the number of whitefly adults was counted in each evaluation, by slowly turning the leaflet upside-down in order to prevent the escape of the insects. To proceed the counting of nymphs, 10 leaflets were collected per plot, from the middle and lower thirds of random soybean plants, stored in separate paper bags and sent for quantification in laboratory with the aid of a Zeiss Discovery.V12 digital magnifying glass.

2.5 Statistical Analysis

Control efficiency for each insecticide treatment was assessed through the equation of Abbott (1925), with the obtained values being submitted to variance analysis (ANOVA) and to the mean separation test of Scott-Knott ($P \leq 0.05$). All statistical analyses were carried out using the softwares Microsoft Excel® (2010) and SAS® (2002).

3. Results and Discussion

3.1 Experiment I

Whitefly population on Experiment I was well estabilished in the soybean field at the moment of the first spray, with an average of 9.68 adults leaflet^{-1} and 1.20 nymphs leaflet^{-1} (Table 2). Despite this condition of high infestation, treatments T4 (cyantraniliprole + lambda-cyhalothrin 100 + 7.5 g ha^{-1}) and T6 (imidcaloprid + lambda-cyhalothrin 105 + 7.5 g ha^{-1}) were highly efficient in suppressing adult population at the first evaluation (5 DA1A), reducing it to 1.55 and 2.08 adults leaflet^{-1}, respectively. The fast control effect provided by these treatments is probably related to the presence of the active ingredient lambda-cyhalothrin, which is particularly effective in the control of sucking pests (*e.g.*, stink bugs; Marques, 2019) and, as a pyrethroid, is known to cause a fast *knockdown* effect on the insects due to its mode of action (sodium channel modulator; see Table 1, Salgado, 2013).

Table 2. Mean number (M) of living adults and nymphs leaflet^{-1} and control efficiency (CE%) of *Bemisia tabaci* adults and nymphs in response to the treatments sprayed on soybean plants under field conditions in Experiment I. Santa Cruz do Sul, RS, Brazil

Treataments	**5 DA1S**[1]		**10 DA1S**		**5 DA2S**		**10 DA2S**		**15 DA2S**		**20 DA2S**		**Mean CE%**
	M[2]	**CE%**	**M**	**CE%**	**M**	**CE%**	**M**	**CE%**	**M**	**CE%**	**M**	**CE%**	
Adults													
Acetamiprid + pyriproxyfen	3.30 b	65.89	14.18 a	42.38	2.30 a	47.43	4.68 a	0.00	5.58 a	20.64	7.78 a	0.00	29.39
Spiromesifen	6.00 a	37.98	15.23 a	38.11	1.90 a	56.57	4.88 a	0.00	4.43 a	37.01	5.13 a	30.03	33.28
Cyantraniliprole	3.88 b	59.95	15.50 a	36.99	1.80 a	58.86	5.78 a	0.00	4.80 a	31.67	6.78 a	7.51	32.50
Cyantraniliprole + lambda-cyhalothrin	1.55 b	83.98	6.29 b	74.44	0.68 a	84.57	3.70 a	20.86	2.83 a	59.79	4.34 a	40.78	60.74
Pymetrozine	4.98 b	48.58	9.50 b	61.38	2.15 a	50.86	5.33 a	0.00	3.35 a	52.31	4.78 a	34.81	41.32
Imidacloprid + lambda-cyhalothrin	2.08 b	78.55	6.03 b	75.51	1.45 a	66.86	3.78 a	19.25	2.18 a	69.04	4.35 a	40.61	58.30
Acetamiprid + bifenthrin	3.25 b	66.41	10.58 b	57.01	3.40 a	22.29	2.75 a	41.18	2.68 a	61.92	2.75 a	62.46	49.76
Cyantraniliprole + abamectin	4.93 b	49.10	14.88 a	39.53	3.63 a	17.14	5.03 a	0.00	4.35 a	38.08	4.75 a	35.15	29.83
Untreated control	9.68 a	-	24.60 a	-	4.38 a	-	4.68 a	-	7.03 a	-	7.33 a	-	-
CV (%) [3]	21.00	-	27.62	-	31.62	-	25.42	-	22.6	-	27.7	-	-
Nymphs													
Acetamiprid + pyriproxyfen	0.88 a	27.08	0.23 a	75.68	0.00 a	100.00	-[4]	-[4]	0.78 a	78.91	0.40 a	97.71	75.88
Spiromesifen	1.10 a	8.33	2.18 a	0.00	0.13 a	94.25	-	-	0.70 a	80.95	3.70 a	78.83	52.47
Cyantraniliprole	1.28 a	0.00	0.78 a	16.22	1.93 a	11.49	-	-	1.70 a	53.74	8.50 a	51.36	26.56
Cyantraniliprole + lambda-cyhalothrin	1.23 a	0.00	0.10 a	89.19	0.40 a	81.61	-	-	0.23 a	93.88	0.33 a	98.14	72.56
Pymetrozine	1.30 a	0.00	0.30 a	67.57	2.78 a	0.00	-	-	1.65 a	55.10	5.85 a	66.52	37.84
Imidacloprid + lambda-cyhalothrin	1.33 a	0.00	0.28 a	70.27	1.70 a	21.84	-	-	1.58 a	57.14	1.73 a	90.13	47.88
Acetamiprid + bifenthrin	0.15 a	87.50	0.58 a	37.84	2.15 a	1.15	-	-	0.75 a	79.59	2.20 a	87.41	58.70
Cyantraniliprole + abamectin	1.33 a	0.00	0.30 a	67.57	1.08 a	50.57	-	-	0.60 a	83.67	2.18 a	87.55	57.87
Untreated control	1.20 a	-	0.93 a	-	2.18 a	-	-	-	3.68 a	-	17.48 a	-	-
CV (%) [3]	26.78	-	39.98	-	41.01	-	-	-	43.5	-	66.01	-	-

Note. [1]DAS = Days after spraying. [2]Means followed by the same letter do not differ among themselves by the Scott-Knott test ($P \leq 0.05$). [3]CV (%) = Coefficient of variation. [4]Lost plot.

The same outcome was verified after the second spray, when treatments T4 (cyantraniliprole + lambda-cyhalothrin 100 + 7.5 g ha^{-1}) and T6 (imidcaloprid + lambda-cyhalothrin 105 + 7.5 g ha^{-1}) kept *B. tabaci* population under 0.68 and 1.45 adults leaflet^{-1}, respectively, and continued to provide the highest contol efficiencies among all treatments (Table 2). On the following evaluations, however, the control efficacy of these treatments steadily descreased, denoting its low potential for residual control; treatment T7 (acetamiprid + bifenthrin 40 + 40 g ha^{-1}), on the other hand, showed long residual effect, reaching the highest control efficiency among all treatments at 20 DA2A (62.46%) and keeping whitefly population under 2.75 adults leaflet^{-1}. The presence of the active ingredient acetamiprid in treatment T7 is probably the cause of such outcome, since neonicotinoids are known to provide a long residual control effect (Salgado, 2013).

Treatment T1 (acetamiprid + pyriproxyfen 60 + 30 g ha^{-1}) was the most efficient treatment in the control of *B. tabaci* nymphs, presenting an average mortality of 75.88% and nearly totally suppressing its population on the last evaluation (0.4 nymphs leaflet^{-1}); whitefly adults, however, were poorly controlled by this treatment, reaching an average control efficiency of just 29.39% (Table 2). Such results, though seemingly contracditory, are expected from treatments containing the active ingredient pyriproxyfen, as showed by Valle, Lourenção, and Novo (2002), and Mesquita, Azevedo, Sobrinho, and Guimarães (2007): both works found pyriproxyfen to be highly efficient in the control of nymphs, partly due to its translaminar action (which enables it to reach the abaxial side of the leaves, where whitefly nymphs are located), but with little to none control effect on whitefly adults.

But how can an insecticide present both the lowest and highest performances on the same pest species, according to the life stage on which it is? The answer is actually quite simple, and is related to the mode of action of pyriproxyfen inside the insect's body. As a substance that mimics the juvenile hormone in order to cause physiological disorder (also known as *growth regulator*), this insecticide has its action limited to the early stages of the *B. tabaci* life cycle (see Supplementary Figure 1), since the juvenile hormone plays no major role in the metabolism of the adult (Gallo et al., 2002). Additionally, the other active ingredient composing treatment T1 (acetamiprid 60 g ha^{-1}), though fairly efficient in the control of whitefly adults when associated to the pyrethroid bifenthrin (as in Treatment T7; see Table 2), was not able to keep a high level of adult mortality by its own.

Similarly to the observed in the adult population, treatment T4 (cyantraniliprole + lambda-cyhalothrin 100 + 7.5 g ha^{-1}) showed high efficacy in the control of *B. tabaci* nymphs, leading to an almost total mortality of individuals at 20 DA2S (0.33 nymphs leaflet^{-1}); however, when used isolated, the insecticide cyantraniliprole (Treatment T3) presented the lowest performance on control of *B. tabaci* nymphs, providing an average control efficiency of only 26.56% (against 72.56% when combined with lambda-cyhalothrin, as in Treatment 4; see Table 2). Despite being widely employed to control Hemipteran pests, this anthranilic diamide insecticide has been reported as increasingly inefficient in the control of *B. tabaci*, with field resistance recently confirmed in China (R. Wang, J. Wang, Che, & Luo, 2018); thus, similar genetic traits in the infesting population surveyed in our work coud be responsible for the lack of control observed for this treatment, though further research would be needed in order to confirm this hypothesis.

3.2 Experiment II

B. tabaci population on Experiment II at the spray moment was at a lower level than on Experiment I, with an average of 0.85 adults leaflet^{-1} and 0.7 nymphs leaflet^{-1} (Table 3). As a consequence, the means of control efficiency were overall higher on Experiment II (especially for whitefly adults), although late sowing dates (as carried out on this field) tend to favor whitefly infestation on soybean due to favorable climatic conditions (Marabi et al., 2017) such as higher mean temperatures (see Lapidot, 2007, according to whom adult emergence does not occur below 17 ºC) and lesser relatively humidity and rainfall (Gupta, Mahapatra, Sanjoy, & Roshan, 1997) during the soybean growth stage when whitefly infestation reaches its peak (R1 or beginning of reproductive phase; Suekane, Degrande, Melo, Azambuja, & Menegati, 2018). While there is no defined *economic injury level* for *B. tabaci* on soybean crops to-date, this results attest the importance of early sprayings at the infestation onset.

Table 3. Mean number (M) of living adults and nymphs leaflet^{-1} and control efficiency (CE%) of *Bemisia tabaci* adults and nymphs in response to the treatments sprayed on soybean plants under field conditions in Experiment II. Santa Cruz do Sul, RS, Brazil

Treatements	5 DA1S[1]		10 DA1S		5 DA2S		10 DA2S		15 DA2S		20 DA2S		Mean CE%
	M[2]	CE%	M	CE%	M	CE%	M	CE%	M	CE%	M	CE%	
Adults													
Acetamiprid + pyriproxyfen	0.40 a	52.94	0.35 b	58.82	1.15 a	42.50	0.65 a	61.76	1.43 a	0.00	-[4]	-[4]	43.20
Spiromesifen	0.38 a	55.88	0.25 b	70.59	1.45 a	27.50	1.65 a	2.94	1.08 a	17.31	-	-	34.84
Cyantraniliprole	0.43 a	50.00	0.23 b	73.53	0.40 a	80.00	0.80 a	52.94	0.65 a	50.00	-	-	61.29
Cyantraniliprole + lambda-cyhalothrin	0.23 a	73.53	0.33 b	61.76	0.28 a	86.25	0.78 a	54.41	0.33 a	75.00	-	-	70.19
Pymetrozine	0.30 a	64.71	0.25 b	70.59	1.13 a	43.75	0.65 a	61.76	0.50 a	61.54	-	-	60.47
Imidacloprid + lambda-cyhalothrin	0.43 a	50.00	0.35 b	58.82	0.90 a	55.00	0.90 a	47.06	0.65 a	50.00	-	-	52.18
Acetamiprid + bifenthrin	0.30 a	64.71	0.63 a	26.47	0.53 a	73.75	1.53 a	10.29	1.05 a	19.23	-	-	38.89
Cyantraniliprole + abamectin	0.50 a	41.18	0.35 b	58.82	0.98 a	51.25	0.48 a	72.06	0.60 a	53.85	-	-	55.43
Untreated control	0.85 a	-	0.85 a	-	2.00 a	-	1.70 a	-	1.30 a	-	-	-	-
CV (%) [3]	29.16	-	-	-	24.92	-	27.82	-	20.59	-	-	-	-
Nymphs													
Acetamiprid + pyriproxyfen	0.78 a	0.00	1.28 a	47.42	-[4]	-[4]	-[4]	-[4]	0.65 b	85.87	0.00 c	100.00	58.32
Spiromesifen	0.68 a	3.57	1.88 a	22.68	-	-	-	-	3.38 a	26.63	0.43 c	73.44	31.58
Cyantraniliprole	1.25 a	0.00	2.23 a	8.25	-	-	-	-	4.15 a	9.78	1.13 b	29.69	11.93
Cyantraniliprole + lambda-cyhalothrin	0.90 a	0.00	1.50 a	38.14	-	-	-	-	1.28 b	72.28	0.78 b	51.56	40.50
Pymetrozine	1.60 a	0.00	0.90 a	62.89	-	-	-	-	5.63 a	0.00	3.23 a	0.00	15.72
Imidacloprid + lambda-cyhalothrin	0.48 a	32.14	1.03 a	57.73	-	-	-	-	4.88 a	0.00	2.88 a	0.00	22.47
Acetamiprid + bifenthrin	0.58 a	17.86	1.68 a	30.93	-	-	-	-	2.18 b	52.72	1.28 b	20.31	30.46
Cyantraniliprole + abamectin	0.50 a	28.57	1.98 a	18.56	-	-	-	-	2.75 a	40.22	3.35 a	0.00	21.84
Untreated control	0.70 a	-	2.43 a	-	-	-	-	-	4.60 a	-	1.60 b	-	-
CV (%) [3]	20.69	-	19.74	-	-	-	-	-	27.5	-	22.91	-	-

Note. [1]DAS = Days after spraying. [2]Means followed by the same letter do not differ among themselves by the Scott-Knott test (P > 0.05). [3]CV (%) = Coefficient of variation. [4]Lost plot.

Agreeing with the results found on Experiment I, treatment T4 (cyantraniliprole + lambda-cyhalothrin 100 + 7.5 g ha^{-1}) presentend the highest average control efficiency (70%), keeping the population of whitefly adults at low levels (under 0.78 adults leaflet^{-1}) in all evaluations. On the other hand, treatment T2 (spiromesifen 144 g ha^{-1}) showed the lowest performance among all treatments, providing only 34.84% of average adult mortality (Table

3). Though proved to be very effective against *B. tabaci* populations across the world, this insecticide has been recently linked to field resistance cases in Spain (Bielza, Moreno, Belando, Grávalos, Izquierdo, & Nauen, 2019), which may be related to the lack of control found in the present study.

Regarding the control of *B. tabaci* nymphs, treatment T1 (acetamiprid + pyriproxyfen 60+30 g ha^{-1}) continued to provide the highest control efficiencies, reaching 100% of nymph mortality at 20 DA2S. Conversevely, treatment T3 (cyantraniliprole 100 g ha^{-1}) repeated the poor performance of Experiment I, presenting only 11.93% of average control efficiency and confirming its low efficacy in the control of nymphs when used isolated. *B. tabaci* nymph's mortality provided by treatment T5 (pymetrozine 200 g ha^{-1}) was also considerably low, especially on the last evaluations (Table 3); accordingly, resistance to pymetrozine has been reported in field strains of *B. tabaci,* either in specific form or in cross-resistance with neonicotinoids (Gorman et al., 2010).

3.3 Combined Analysis

As illustrated in the average means of control efficiency (Table 4), the two experiments agreed on the main outcomes, despite being carried out under different *B. tabaci* infestation levels. Treatment T4 (cyantraniliprole + lambda-cyhalothrin 100 + 7.5 g ha^{-1}) led to the highest levels of adult mortality in both experiments, while treatment T1 (acetamiprid + pyriproxyfen 60 + 30 g ha^{-1}) performed similarly on whitefly nymphs; nonetheless, given the reasonable nymph reduction provided also by treatment T4 (see Figure 1), the combination cyantraniliprole + lambda-cyhalothrin (100 + 7.5 g ha^{-1}) can be pointed out as the most efficient current alternative for whitefly control on soybean crops, regardless of the infestation level and life phase of the insect. Furthermore, the cost of this treatment (31.06 USD ha^{-1}) is fairly low when compared to cyantraniliprole 100 g ha^{-1} and pymetrozine 200 g ha^{-1}, for instance (see Table 1); other less-costly treatments, such as imidcaloprid + lambda-cyhalothrin 105 + 7.5 g ha^{-1} (9.39 USD ha^{-1}) and acetamiprid + bifenthrin 40 + 40 g ha^{-1} (12.37 USD ha^{-1}), provided adult and nymph mortalities too low to justify its use.

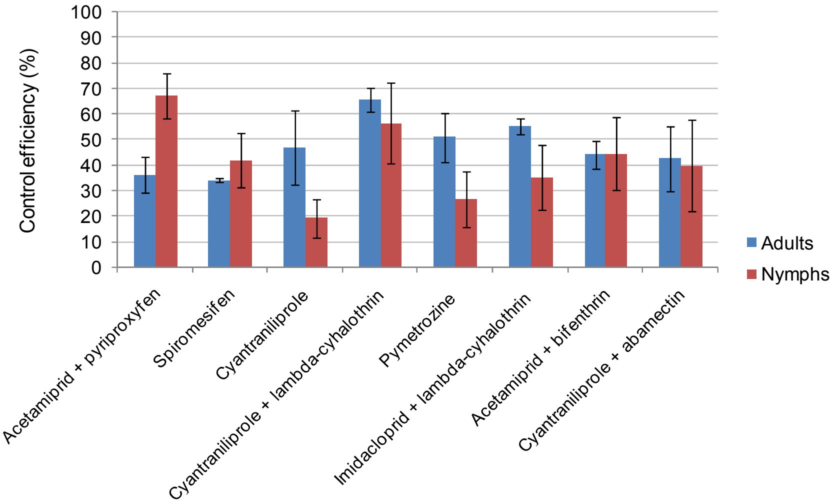
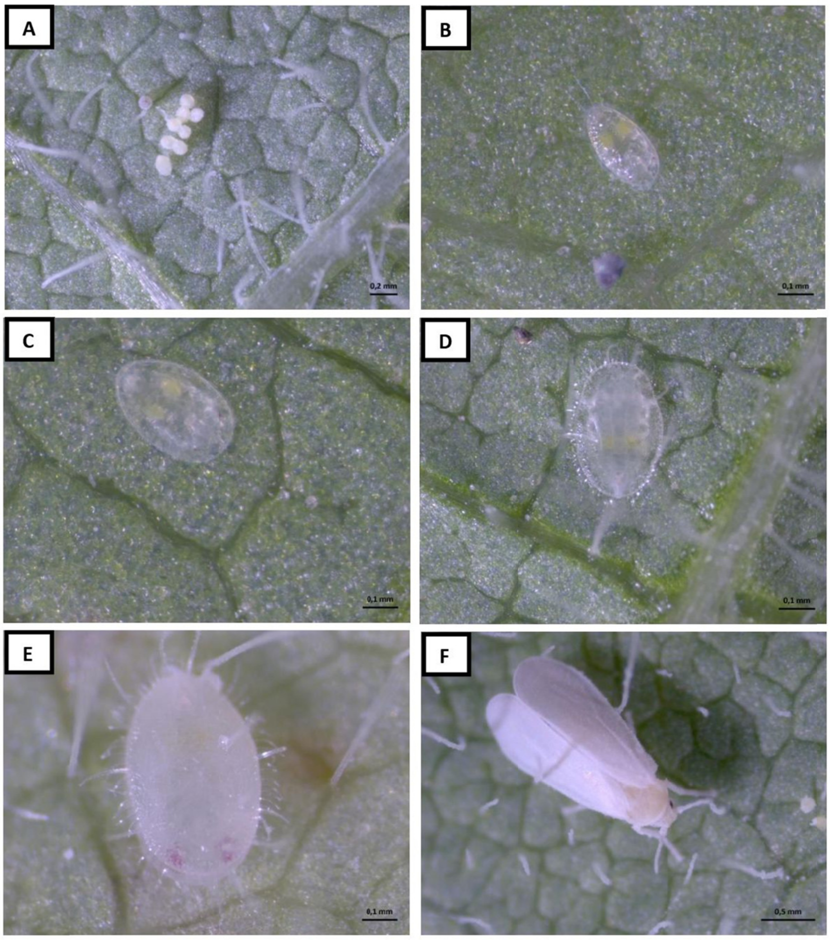


Figure 1. Average means and standard deviation for control efficiency (CE%) of *Bemisia tabaci* adults and nymphs in response to the treatments sprayed on soybean plants under field conditions. Santa Cruz do Sul, RS, Brazil

Table 4. Means of control efficiency (CE%) of *Bemisia tabaci* adults and nymphs in response to the treatments sprayed on soybean plants in Experiment I and Experiment II, under field conditions, and in average means. Santa Cruz do Sul, RS, Brazil

Treataments	**Experiment I (CE%)**	**Experiment II (CE%)**	**Average mean (CE%)**
Adults			
Acetamiprid + pyriproxyfen	29.39	43.20	36.30
Spiromesifen	33.28	34.84	34.06
Cyantraniliprole	32.50	61.29	46.90
Cyantraniliprole + lambda-cyhalothrin	60.74	70.19	65.47
Pymetrozine	41.32	60.47	50.90
Imidacloprid + lambda-cyhalothrin	58.30	52.18	55.24
Acetamiprid + bifenthrin	49.76	38.89	44.33
Cyantraniliprole + abamectin	29.83	55.43	42.63
Untreated control	-	-	-
Nymphs			
Acetamiprid + pyriproxyfen	75.88	58.32	67.10
Spiromesifen	52.47	31.58	42.03
Cyantraniliprole	26.56	11.93	19.25
Cyantraniliprole + lambda-cyhalothrin	72.56	40.50	56.53
Pymetrozine	37.84	15.72	26.78
Imidacloprid + lambda-cyhalothrin	47.88	22.47	35.18
Acetamiprid + bifenthrin	58.70	30.46	44.58
Cyantraniliprole + abamectin	57.87	21.84	39.86
Untreated control	-	-	-



Supplementary Figure 1. Life stages of *Bemisia tabaci*: A) Egg phase; B) First nymphal phase; C) Second nymphal phase; D) Third nymphal phase; E) Fourth nymphal phase; F) Adult phase. Photos by H. Pozebon

Nothwithstanding the similarity of results, the overall higher adult mortalities obtained in Experiment II (Table 4) and the enhancement of control efficiency observed after the second spray indicate that sequential sprays beginning at the infestation onset are a key factor for the control of *B. tabaci* on soybean crops. Accordingly, the threshold for whitefly control on soybean should be set at a very early stage of the infestation, in order to ensure control efficiency and prevent resistance development—which is fast increasing across the world and represents the main likely cause for the lack of control observed in most treatments of the present study, being probably related to enhanced activity of detoxification enzymes and target-site insensitivity in certain *B. tabaci* strains (Zhang, Kong, & Zeng, 2015). Raising recommended doses to face these problems, though a possible solution for low-performance insecticides, could exceedingly increase control costs with little guarantee of enhanced control efficiency.

Sequential sprays are particularly important for the performance of pyrethroid insecticides, which rely basically on fast *knockdown* effect (Salgado, 2013); neonicotinoids, on the other hand, provide longer residual effect allied to robust plant sistemicity (Stamm et al., 2016), which may be linked to a higher control efficiency of nymphs, as observed in some of the treatments (*e.g.*, acetamiprid in treatment T1). Whitefly nymphs infesting soybean are concentrated in the middle and lower thirds of the plants (Czepack et al., 2018), in the abaxial side of the leaflets and in the middle and bottom areas of its surface (Pozebon et al., 2019), due to the female's habit of feeding and ovipositing in the upper and younger leaves of the soybean plants; therefore, *B. tabaci* adults are more exposed to direct contact with the insecticide spray, while the control of the sheltered nymphs relies more heavily on the efficacy of the insecticide translocation inside the plant.

Pyrethroids as a whole are preferred by the growers due to their fast and visible effect; however, their broad spectrum of action may also result in harmful effects on natural enemies, such as parasitoids (*e.g.*, *Encarcia formosa*; Vieira et al., 2012) and predators (*e.g.*, *Orius tristicolor*; Kon, 2016). The active ingredient abamectin (present in treatment T8; see Table 1), on the other hand, has been proved innocuous to whitefly predators (*e.g.*, *Lasiochilus* sp.; Bacci et al., 2007); the control efficiency provided by this treatment on the present study, however, remained at a low level and do not justify its use. Microbiological insecticides have also been proposed as an alterantive to chemical control, with the fungus *Beauveria bassiana* being especially efficient in the control of *B. tabaci* nymphs (Alves et al., 2001; Azevedo, Guimarães, Braga Sobrinho, & Lima, 2005; Neto & Barros, 2016); nonetheless, the particularities involved in its use (*e.g.*, slow action, high cost and strong dependence on ideal environmental conditions; Vidal, Fargues, Rougier & Smits, 2003) prevent a broader adoption of such strategies.

In the current scenario of global agriculture and crop protection, the use of chemical insecticides remains the most efficient and economically viable control strategy for *B. tabaci* on soybean. However, the increasing failures of control and growing occurrence of resistant strains set an alert to the long-term sustaintability of this method, raising the need for new alternative methods inside the *integrated pest management* (IPM) and *integrated resistance management* (IRM) approaches for this pest. Accordingly, further studies should be devoted to the establishment of an *economic injury level* for whitefly on soybean crops, which represents the first step towards a standardized monitoring and control program for any major agricultural pest.

4. Conclusions

(1) Cyantraniliprole + lambda-cyhalothrin (100 + 7.5 g ha^{-1}) is the most efficient treatment for the control of *B. tabaci* adults, reaching 65% of control efficiency and keeping the infestation level under 6.29 adults leaflet^{-1};

(2) Acetamiprid + pyriproxyfen (60 + 30 g ha^{-1}) is the most efficient treatment for the control of *B. tabaci* nymphs, reaching 67% of control efficiency and keeping the infestation level under 1.28 nymphs leaflet^{-1};

(3) Sequential sprays beginning at the infestation onset enhance control efficiency.

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