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Repellency of selected biorational insecticides to potato psyllid, *Bactericera cockerelli* (Hemiptera: *Psyllidae*)

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ABSTRACT

Bactericera cockerelli has recently become a major concern because of its direct feeding and vectoring of bacterial diseases in many solanaceous crops. The repellency of four biorational insecticides, MOI-201 (a Chinese medicine plant extract), Requiem (a plant extract of *Chenopodium ambrosioides*), BugOil (a mixture of four plant essential oils), and SunSpray oil (a mineral oil), to *B. cockerelli* adults was tested on tomato. In a no-choice test, all the insecticides had significant repellency to adults and deterred oviposition as compared with untreated controls. Of the four insecticides, the two oils showed a stronger repellency to adults and deterred oviposition more strongly than Requiem or MOI-201. In a choice test, all insecticides had significant repellency to adults and deterred oviposition compared to untreated controls. Of the four tested insecticides, <1 adults and no eggs were found on the leaves treated with SunSpray Oil, BugOil or Requiem 3 d after treatment. The repellency rates of these three insecticides were 77.2–95.4%. MOI-201 also repelled adults significantly and deterred oviposition compared to untreated controls even though it was the least effective insecticide among the four evaluated. In conclusion, all four insecticides tested showed significant repellency to *B. cockerelli* adults and deterred oviposition, especially the two oils. The overall repellency to potato psyllid adults can be arranged in a descending order of SunSpray oil > BugOil > Requiem > MOI-201. These insecticides could be used in integrated pest management programs targeted against the potato psyllid on solanaceous crops.

1. Introduction

The potato psyllid, *Bactericera cockerelli* (Sulc) (Hemiptera: *Psyllidae*), has recently become a major concern due to its destructive impact on potato, tomato, and several other solanaceous crops in the United States, Mexico, Central America, and New Zealand (Liu and Trumble, 2006; Munyaneza et al., 2007a,b; Liefting et al., 2008). This piercing–sucking insect has recently been shown to transmit the bacterial pathogen "*Candidatus* Liberibacter *solanacearum*" that causes a newly emerging potato disease named Zebra Chip (Hansen et al., 2008; Liefting et al., 2008, 2009; Lin et al., 2009). This disease is characterized by distinct internal brown discoloration in potato tubers when sliced and commercially unacceptable dark stripes and streaks when the affected tubers are processed to produce potato chips (Munyaneza et al., 2007a, b, 2009). Zebra Chip disease has caused millions of dollars in losses to the potato industry in the United States, especially in Texas (Munyaneza et al., 2007a, b, 2009). In California, the potato psyllid can cause up to 80% loss on tomato crops due to direct feeding and the bacterium it vectors (Liu and Trumble, 2006).

At present, applications of insecticides are the only effective means for management of *B. cockerelli* and the diseases it vectors to solanaceous crops, especially potato and tomato. Intensive use of broad-spectrum insecticides is often costly, decimates natural enemies, results in insecticide resistance, environmental contamination and sometimes causes secondary pest outbreaks (Liu and Stansly, 1995a, b, c). Biorational insecticides include botanical extracts and their synthetics, bacteria, viruses, fungi and protozoa, as well as chemical analogues of naturally occurring biochemicals, such as pheromones and insect growth regulators, and have been used to control numerous species of insect pests (Djerassi et al., 1974; Schmutterer, 1990, 1995; Davidson et al., 1991; Ascher, 1993; Haseeb et al., 2004). Insecticidal oils, including those of botanical or mineral origin, are favorable biorational pesticides for management of numerous pest insects, especially soft-bodied

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insects. In addition, many botanical insecticides and insecticidal oils also act as insect repellents (Butler et al., 1989, 1993; Larew and Locke, 1990; Schmutterer, 1990, 1995; Stansly and Liu, 1994; Liu and Stansly, 1995c; Liang and Liu, 2002; Plant Impact plc, 2006).

In Texas, management of potato Zebra Chip disease mainly relies on targeting *B. cockerelli* occurring in the potato crop. It has been shown, however, that this insect can acquire and transmit *Ca.* L. solanacearum in ˜2 h (J.E. Munyaneza, unpublished data), suggesting that insecticides that can knock down *B. cockerelli* quickly are needed to effectively prevent disease transmission. Repelling *B. cockerelli* adults from landing and feeding on host plants and deterring oviposition could help eliminate or reduce transmission of the bacterial pathogen and reduce Zebra Chip disease incidence and other related diseases. In this study, we investigated the repellency to *B. cockerelli* adults of four biorational insecticides (three plant extract-based insecticides and one mineral oil) and their deterrent effects on *B. cockerelli* oviposition on tomato plants under greenhouse and laboratory conditions.

2. Materials and methods

2.1. Source of potato psyllids and tomato plants

Potato psyllids used in the study were obtained from a psyllid colony that had been maintained in a screen cage on tomato plants for >2 years at the Texas AgriLife Research station at Weslaco, Texas. Tomato, *S. lycopersicum* L. (variety 'Florida Lanai'), was seeded first in a foam tray with cone-shaped pots (3 × 3 × 4 cm) in a greenhouse at 28–32 °C and in natural lighting conditions. One week after germination, the tomato seedlings were individually transplanted into 1 L plastic pots. The seedlings were fertilized weekly with 0.6 g L^{-1} Water Soluble Plant Food (N:P:*K* = 15:30:15) (Chemisco, Division of United Industries Corp. St. Louis, MO, USA) and watered as needed. Four-week old tomato plants were used in all experiments.

2.2. Insecticides and bioassays

Concentrations and manufacturers of the four botanical products (MOI-201, Requiem, BugOil and SunSpray Oil) evaluated during the study are indicated in Table 1. Deionized water was used for the untreated controls. Each of the four insecticides was prepared by adding the material slowly to a glass beaker filled with appropriate amount water, while being stirred with a magnetic plate. All bioassays were carried out under both greenhouse (28–32 °C and natural light) and laboratory [26.7 ± 2.0 °C, 75 ± 5% RH with a photoperiod of 14:10 (L:D) h] conditions.

For the laboratory bioassays, the top 3 fully expanded leaves (the terminal leaflets) of the 4-week old tomato plants were excised from the plants and used in the study. The leaves were dipped in each insecticide solution for 5 s and then transferred to a paper towel for air drying. The petioles of the air-dried treated leaves were then inserted into a 50 ml KIMAX cone-shaped flask filled with water. The gap around the flask opening and the leaf petiole was stuffed with cotton balls to prevent the psyllid adults from drowning in the solution flask.

2.3. No-choice test: persistence of residues

In this test, the repellent effects of the residues of the four insecticides on *B. cockerelli* adults and oviposition were examined under greenhouse conditions. Twenty 4-week old tomato plants were used for this test. All the leaves on each plant were removed, except the top 5 fully expanded leaves. The insecticides MOI-201, Requiem, BugOil, SunSpray and deionized water were sprayed on both leaf surfaces until run-off. The treated leaves were left to air dry naturally in the greenhouse, and were randomly assigned to one of the 4 residual treatments: leaves exposed to potato psyllids 1, 2, 4 or 7 days after insecticide treatment. Deionized water was used as the control treatment. A leaf clip-on cage (5 cm in diameter, 3 cm in height) was placed on each of the treated leaves and 10–15 pairs of *B. cockerelli* adults (males and females, ≤15 d old) were introduced into each cage. The longevity of the adults was around 60 days on tomato and potato under laboratory conditions; and the adults at this age were chosen because they were relatively young and active and the females deposit the most eggs (Yang and Liu, 2009). Twenty four hours after introduction, the numbers of *B. cockerelli* adults on each leaf or cage surface were recorded with the help of a 10x optical glass binocular magnifier (OptiVISOR, Donegan Optical Company, Lenexa, KS, USA). The percentage of potato psyllid adults on each leaf was calculated by dividing number of adults on each treated leaf surface with total number of potato psyllid adults introduced in the cage. The plant leaves were excised from the plants and numbers of eggs laid on the leaves were counted under a stereomicroscope. Each insecticide treatment was replicated four times.

2.4. Choice test

The choice test was conducted under laboratory conditions. Four-week old tomato plants (10–12 leaves) were used in this test. The top four fully expanded leaves were detached from the plants, and dipped in one of the four insecticide dilutions or deionized water (untreated control) for 5 s. After the leaves had air-dried (˜2 h), the leaves were individually inserted into flasks (as described above). The treated leaves (one from each of the five treatments) were simultaneously placed on a rotary wood board (50 cm in diameter) in a circle in a large cage (60 × 60 × 60 cm) and the leaves were placed ≈10 cm apart. Twenty-five male and female adults of *B. cockerelli* (≤15 d old) were placed in a Petri dish in the centre of the rotary board in the cage so that the adults were allowed to freely jump or fly around in the cage, mate, land or feed on the treated leaves of their choice. Numbers of *B. cockerelli* adults were recorded by gently turning the leaves 24, 48 and 72 h after release. The leaves with *B. cockerelli* adults were shaken to force them to relocate among the treated leaves in the cage. At the end of the experiment, all leaves were removed from the cage and numbers of eggs on each leaf were counted under the stereomicroscope. The percentage of potato psyllid adults or eggs on each treated leaf was calculated by dividing the number of adults or eggs on each treated leaf by the total number of potato psyllid adults or eggs of the five treatments. The test was replicated four times.

Table 1
Insecticides and concentrations used in this study.

Material	Active ingredient	Concentration	Manufacturer
MOI-201	a Chinese medicine plant extract; active ingredient: 0.6% oxymatrine	1:800 (vol:vol)	Marrone Organic Innovations, Davis, CA
Requiem	25% of essential oil extract of *Chenopodium ambrosioides* nr. *ambrosiodes*	4.3 g L^{-1}	AgraQuest, Inc., Davis, CA
BugOil	94% canola oil, 0.6% thyme oil (*Thymus vulgaris*), 0.6% tagetes oil (*Tagetes erecta*) and 0.001% wintergreen oil (*Gaultheria procumbens*)	1% (vol:vol)	Arysta LifeScience North America, Cary, NC
SunSpray Ultra-Fine Oil	98.8% Paraffinic Oil (92.0% unsulfonated residue, 212 °C, 50% distillation point and 1.2% emulsifier (inert ingredient)	0.5% (vol:vol)	Sun Company, Philadelphia, PA

2.5. Data analysis

The repellency data (%) in the no-choice test were arcsine-transformed and analyzed using a factorial ANOVA with four insecticides over four different residual ages of the materials applied on the leaves (GenStat Release 9.1; Lawes Agricultural Trust, 2010), and the data in the water control were not included in the analysis as the data was mostly zero values. Numbers of adults and eggs on treated leaves in different treatments in the choice test were subject to a two-way ANOVA, and means were separated using the least significant difference test at $P = 0.05$ (LSD, SAS Institute, 2000). Repellency data in the choice test were computed under the following assumption: the four insecticides and water had the same repellency effect and the treated leaves that did not have any adults, had an equal number to the mean number of adults among the treatments, had a 100% repellency effect, or had no (0%) repellency effect. Therefore, the following formula was used: Repellency (%) = (Mi − Mt)/(0-Mt) × 100; Mi was the mean number of adults in each treatment, and Mt was the overall mean number of adults among the treatments. Any treatment with a Repellency (%) ≤ 0 was not repellent or negatively repellent (= attractive) to potato psyllids.

3. Results

3.1. No-choice test: persistence of residues

Repellency results of the insecticides on potato psyllid adults differed significantly among the five treatments (SED = 2.88, *LSD* = *5.81*; $P = 0.05$) (Table 2). The repellency among the residual ages for the tested materials varied the same trend as among the treatments (Table 2). The interactions of the materials and residual ages were not significantly different (SED = 5.77, *LSD* = *11.62*; $P = 0.056$). Repellency levels were all significantly different among the four insecticides at all residual ages except for BugOil and SunSpray Oil that their repellency rates were not different with the strongest overall repellency to potato psyllid adults. However, it appears that this oil lost its repellency when its residue gradually degraded, 74.5% of adults were repelled from the treated leaves with 4-d old residue and 47.5% from the leaves with 7 d old residue. BugOil showed strong repellency in 1 d after treatment, and its repellency gradually decreased with the residues degrading. Over 65% of psyllid adults did not land on the leaves with 4-d old residue, and ≈26% on those with 7 d old residue. Requiem had relatively stronger repellency to potato psyllid adults in the first day than MOI-201, and had similar repellency to MOI-201 when the residue was 2 d old or older.

Table 2
Percentage (and arcsine-transformed percentage) *B. cockerelli* adults that were repelled by the residues (1, 2, 4, and 7 d old) of the four insecticides on treated tomato leaves in a no-choice test (exposed for 24 h). The transformed data have been subjected to ANOVA, with the data for the water controls excluded from the analysis.

Product	Residue age				
	1 day	2 days	4 days	7 days	Mean
% repelled					
MOI-201	94.1	66.9	40.0	11.2	**52.8**
Requiem	98.8	80.0	52.5	17.5	**62.2**
BugOil	100	72.1	67.0	25.9	**63.8**
SunSpray oil	100	100	74.5	47.5	**80.5**
Water	1.2	0	0	0	**0.3**
Mean	**78.8**	**63.8**	**44.8**	**20.2**	**51.9**
$\sin^{-1}$(% repelled)$^{1/2}$					
MOI-201	78.1	55.5	38.9	18.0	**47.6**
Requiem	86.8	64.4	46.7	23.3	**55.3**
BugOil	90.0	58.2	49.1	30.4	**56.9**
SunSpray oil	90.0	90.0	60.3	43.4	**70.9**
Water	[3.2]	[0]	[0]	[0]	**[0.8]**
Mean[a]	**86.2**	**671**	**48.8**	**28.8**	**57.7**
	Product		Residue age		Product × residue age
ANOVA $\sin^{-1}$(% repelled)$^{1/2}$					
P	<0.001		<0.001		0.056
DF	3		3		9
SED	2.88		2.88		5.77
LSD ($P = 0.05$)	5.81		5.81		11.62

Note: The means for the water controls are given in square parenthesis to indicate comparisons using given SED and LSD values are not valid.
[a] Values for the water control were not included in the calculation of these mean values.

The number of *B. cockerelli* eggs laid on the treated leaves can be a better indicator of oviposition deterrent effects than repellency to adults. The numbers of eggs oviposited during the 7 d period were significantly different among the treatments ($F_{4,19} = 35.78$ to 98.88; $P < 0.0001$) (Fig. 1). The numbers of eggs found on the leaves treated with SunSpray Oil and BugOil were significantly lower than those treated with Requiem and MOI-201. No eggs were found on the leaves treated with SunSpray Oil residue for as long as 7 days. No eggs were found on the leaves treated with BugOil for 4 days, and only an average of 2.8 eggs per leaf were found on the leaves with 7 d old residue. Also, no eggs were found on the leaves with the residues of Requiem and MOI-201 on the first day, and low numbers of eggs were found on the leaves with older residues as compared with those treated with the two oils, although those were significantly lower than the eggs on the leaves treated with water.

3.2. Choice test

When given five choices, significantly more *B. cockerelli* adults were found away from the leaves treated with the insecticides than from those treated with water 1, 2 and 3 d after treatment (Table 3). Of the four insecticides, Requiem, BugOil, and SunSpray oil had stronger repellent effects than MOI-201. SunSpray Oil and BugOil showed a >90% repellency effect and Requiem had >88% repellency effect. In contrast, although numbers of potato psyllids adults on the MOI-201 treated leaves were less than those on water-treated leaves, this product did not show significant repellency (Table 3).

Similarly, significantly fewer *B. cockerelli* eggs were found on the leaves treated with all four insecticides than on those treated with water (Fig. 2). Of the four insecticides, no eggs were found on

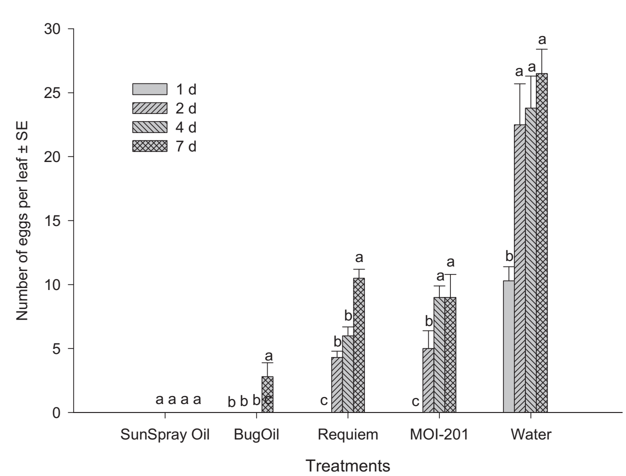

Fig. 1. Numbers of *B. cockerelli* eggs on the tomato leaves treated with four insecticides or water at 1, 2, 4, and 7 d after treatment in a no-choice test. The same letters over the bars among the five treatments on the same day indicate that the means are not significantly different (LSD, $P < 0.05$).

Table 3
Number of *B. cockerelli* adults on tomato leaves and percent of repellency (%) 1, 2, and 3 d after treatment with four insecticides and water in a choice test.

Treatment	1d ($N = 44$)[a]			2d ($N = 34.3$)			3d ($N = 32.8$)		
	No. of adults	SE	% repellency	No. of adults	SE	% repellency	No. of adults	SE	% repellency
SunSpray oil	0.8c	0.3	90.9	0.5c	0.3	92.7	0.3c	0.3	95.4
BugOil	1.0c	0.7	88.6	0.5c	0.5	92.7	0.3c	0.3	95.4
Requiem	2.0c	1.1	77.2	0.8c	0.3	88.4	0.5c	0.3	92.4
MOI-201	12.3b	2.3	−40.1	10.3b	1.3	−49.7	10.3b	1.1	−56.6
Water	27.8a	2.4	−216.6	22.3a	3.5	−224.1	21.5a	2.8	−226.7
$F_{4,19}$	54.20			28.90			49.86		
P	<0.0001			<0.0001			<0.0001		

Means in the same column followed by different letters are significantly different at $P = 0.05$ (LSD test, SAS Institute, 2000).
[a] N: mean number of potato psyllid adults introduced.

Requiem, BugOil, and SunSpray Oil treated leaves after 72 h, which had significantly fewer eggs than those on the MOI-201 treated leaves ($F_{4,19} = 45.59$; $P < 0.0001$) on which only an average of 8.0 eggs were found on each treated leaf at 72 h. In contrast, >100 eggs were found on each water-treated leaf.

4. Discussion

Effective integrated pest management strategies for insect-vectored diseases are aimed at achieving effective control of the target insect pests, whereas minimizing detrimental impacts to non-target beneficial arthropods, the environment and humans. This approach has drawn attention to the use of biorational control of the insect pests in the agricultural ecosystems. Consequently, botanicals have become more desirable compared with conventional synthesized broad-spectrum chemical pesticides due to their low toxicity to environment and beneficial arthropods. In Zebra Chip disease and related disease agroecosystems, where the bacterium, '*Ca.* Liberibacter', is acquired and transmitted by its insect vector in a very short period of time, it would be helpful to reduce the numbers of adults of *B. cockerelli* entering the crop field and quickly infecting host plants. In this study, the four insecticides tested had significant repellent effects on *B. cockerelli* adults, especially the two oils, BugOil and SunSpray oil. The data also showed that SunSpray Oil had the strongest repellency to *B. cockerelli* adults among the four tested insecticides, and had >50% repellency to *B. cockerelli* for up to 7 days under greenhouse conditions.

During the present study, among the three botanical products tested, BugOil had a stronger repellent effect on *B. cockerelli* adults

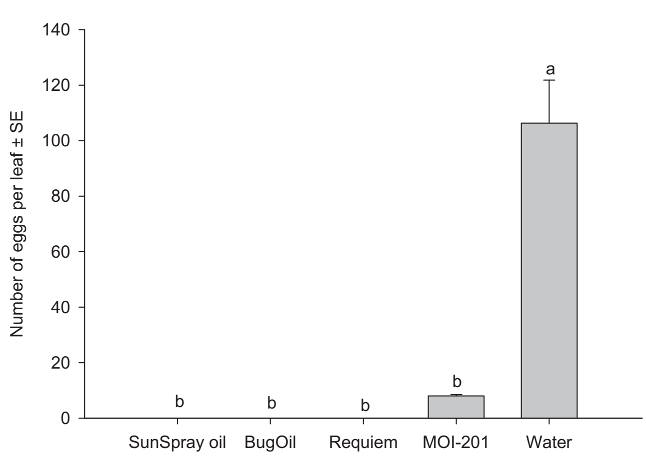

Fig. 2. Numbers of *B. cockerelli* eggs on the tomato leaves treated with four insecticides or water in a choice test. The same letters over the bars among the five treatments indicate that the means are not significantly different (LSD, $P < 0.05$).

under both laboratory and greenhouse conditions. However, the repellency of BugOil to potato psyllid adults appeared to be moderate 2 d and 4 d after treatment, with >50% repellency. However, in the no-choice repellency persistence test <2.2% of all *B. cockerelli* adults landed on the leaves treated with the oil. Additionally, its effectiveness was further enhanced because there was no egg oviposited on the treated leaves, indicating that BugOil also had strong deterrent effects on oviposition. BugOil is a synergistic blend of plant essential oils and it has been claimed to have at least an equal or better control effect against some sap-feeding pests, including mites, whitefly, thrips and aphids, than those of some conventional insecticides as well as providing broad-spectrum pest coverage (Marks, 2006; Plant Impact plc, 2006). Previous studies reported that in some crops, such as tomato, pepper and cucumber, the repellency of the BugOil to whitefly, aphids and mites can last up to 14 days with >75% repellency throughout and with advantages including safety to non-target organisms and beneficial insects. Other advantages of the BugOil are that it is biodegradable, leaves little residue and does not cause taint on crops thus showing a good potential commercial perspective (Marks, 2006; Plant Impact plc, 2006). The active ingredient of BugOil is mainly canola oil, which can be rapidly biodegraded (Marks, 2006; Plant Impact plc, 2006). MOI-201 and Requiem showed relatively moderate repellency to *B. cockerelli* adults as compared to BugOil and SunSpray Oil, and they still showed significant repellency as compared to the water control in the choice test. The Requiem has been shown to effectively control spider mites, mealybug and thrips (Chiasson et al., 2004a, b; Cloyd and Chiasson, 2007). We have found that MOI-201 caused >97% mortality of young (first to third instar) nymphs of the potato psyllid in the laboratory bioassays (Yang and Liu, 2009).

SunSpray Oil showed a stronger repellency to *B. cockerelli* adults than the other three botanical insecticides tested in the present study. Furthermore, no potato psyllid eggs were oviposited on the SunSpray Oil treated leaves in either the choice or no-choice test. Previous studies also demonstrated that SunSpray Oil treated chrysanthemum repelled *Trialeurodes vaporariorum* (Westwood) adults for more than 11 days (Larew and Locke, 1990; Liu and Stansly, 1995a, c). This oil also had significant repellency to *Bemisia tabaci* (Gennadius) on several other crops, including cotton, melon, squash (Butler et al., 1989; Liang and Liu, 2002), and tomato (Liu and Stansly, 1995a, c).

There are several practical points that need to be addressed. Firstly, these products can be used any time when the pest insects exceed the economic threshold, and early application of these insecticides will reduce the infestation of pest insects because of their strong repellency (Butler et al., 1989, 1993; Davidson et al., 1991; Liu and Stansly, 2000, 1995a, c; Cloyd and Chiasson, 2007). Secondly, full coverage of the plant surface with these materials is essential because they are contact-acting (Liu and Stansly, 1995a, c). Thirdly, insecticidal oils have been traditionally tank-mixed with many different pesticides; adding oils to an effective insecticide may even help to delay the development of resistance and increase the efficacy as the oil will kill or repel many insects that are resistant to the insecticide (Liang and Liu, 2002). Fourthly, the repellency effects of the four insecticides decreased with the aging of residues and followed the same trend because the interaction between insecticides and residual ages was not significant when water was excluded, and was significant when water was included, indicating that the interaction factor was water (Table 2). Lastly, caution is necessary when applying oils, especially the SunSpray Oil, under field conditions. In our early studied for management of *B. tabaci* (Gennadius) we found that SunSpray Oil at 5 ml L^{-1} rate could cause phytotoxic damage to some tender leaves on melons, especially in hot conditions (Liu and Stansly, 2000).

In summary, results of the present study clearly showed that the SunSpray Oil and BugOil had significant repellency to *B. cockerelli* under both greenhouse and laboratory conditions. Therefore, SunSpray oil and BugOil have great potential for reducing potato psyllids and thereby reducing Zebra Chip disease and related diseases incidence when used. We believe that biorational insecticides, including the four insecticides evaluated have great potential for management of *B. cockerelli*, although more insecticides should be screened and evaluated under both laboratory and field conditions for additional control of this insect. Furthermore, an integrated potato psyllid management strategy should take into consideration the use of insect resistant varieties, conserving and augmenting biological control agents and avoiding applications of broad-spectrum insecticides.

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