Potential of Essential Oil-Based Pesticides and Detergents for Bed Bug Control

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ABSTRACT The bed bug, (*Cimex lectularius* L.), is a difficult pest to control. Prevalence of insecticide resistance among bed bug populations and concerns over human-insecticide exposure has stimulated the development of alternative bed bug control materials. Many essential oil-based pesticides and detergent insecticides targeting bed bugs have been developed in recent years. We evaluated the efficacy of nine essential oil-based products and two detergents using direct spray and residual contact bioassays in the laboratory. Two conventional insecticides, Temprid SC (imidacloprid and β-cyfluthrin) and Demand CS (λ-cyhalothrin), were used for comparison. Among the 11 nonsynthetic insecticides tested, only EcoRaider (1% geraniol, 1% cedar extract, and 2% sodium lauryl sulfate) and Bed Bug Patrol (0.003% clove oil, 1% peppermint oil, and 1.3% sodium lauryl sulfate) caused >90% mortality of nymphs in direct spray and forced exposure residual assays. However, the efficacy of EcoRaider and Bed Bug Patrol was significantly lower than that of Temprid SC and Demand CS in choice exposure residual bioassay. Direct spray of EcoRaider caused 87% egg mortality, whereas the other nonsynthetic insecticides had little effect on bed bug eggs. EcoRaider and Bed Bug Patrol did not exhibit detectable repellency against bed bugs in the presence of a carbon dioxide source. These findings suggest that EcoRaider and Bed Bug Patrol are potentially useful pesticides for controlling bed bug infestations, but further testing in naturally infested environments is needed.

KEY WORDS bed bug, essential oil, efficacy, repellency

The bed bug (*Cimex lectularius* L.) is a difficult urban pest to control. Despite many control materials and methods being available for bed bug management, insecticide treatments continue to be the most popular (Moore and Miller 2008, Potter 2008, Potter et al. 2013). Many new insecticide products for bed bug control have become available in recent years. Pyrethroid insecticides and combinations of pyrethroids and other classes of insecticides are routinely used by professionals. Hot Shot Bed Bug & Flea aerosol (0.005% γ-cyhalothrin and 0.025% prallethrin) and ready-to-use liquid spray (0.03% λ-cyhalothrin) are commonly used consumer products based on our surveys in bed bug-infested apartments (N. S., unpublished data). These and other sprays that use pyrethroids as active ingredients are not very effective in eradicating bed bugs due to insecticide resistance among bed bug populations (Potter 2005; Romero et al. 2007; Zhu et al. 2010, 2013). There are also general concerns of human-insecticide exposure, as these pesticides are typically applied onto furniture or around sleeping and resting areas.

Over the past 5 yr, "reduced risk" bed bug control materials have been actively sought to meet the urgent need for do-it-yourself bed bug eradication. These reduced risk pesticides pose less risk to human health and the environment than existing conventional alternatives. One group of materials that received particular attention is essential oils. There have been numerous studies examining the potential of essential oils for controlling pests of public health importance (Barcay 2004, Isman and Machial 2006). Among them, thymol (Pandey et al. 2009, Phillips et al. 2010), *trans*-cinnamaldehyde (Cheng et al. 2008, Phillips et al. 2010), citronella oil, citral, geraniol, methyl eugenol, eugenol (clove oil) (Cornelius et al. 1997, Ngoh et al. 1998), citronellal, cotronellol, citronellyl (Ping 2007), catnip oil (Chauhan and Raina 2006), and carvacrol (Panella et al. 2005) have been shown to be efficacious as direct sprays against insects of urban and medical importance. Besides essential oils, some detergent materials were found effective against the German cockroach (*Blattella germanica* L.) (Szumlas 2002, Baldwin and Koehler 2007), the American cockroach (*Periplaneta americana* L.) (Reza et al. 2010), and the blacklegged tick (*Ixodes scapularis* Say) (Allan and Patrican 1995) as direct sprays.

Essential oil-based pesticides and detergents are attractive to both manufacturers and consumers. For manufacturers, it is comparatively easier and less expensive to market products that are generally regarded as safe (GRAS), as these products are exempt

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Table 1. A list of essential oil-based pesticides, detergents, and synthetic insecticides that were used in bioassays

No.	Product trade name	Listed active ingredients	Manufacturer/distributor
1	Bed Bug 911	Sodium lauryl sulfate (3%), sodium chloride (1%), and citric acid (0.2%)	Bedbug 911, Brooklyn, NY
2	Bed Bug Bully	Mint oil (0.25%), clove oil (0.3%), citronella oil (0.4%), and rosemary oil (0.4%)	Optimal Chemical LLC, Tamarac, FL
3	Bed Bug Fix	2-Phenethyl propionate (2%), geraniol (1%), cedar oil (0.3%), eugenol (0.3%), and citronella oil (0.2%)	NuSafe Floor Solutions Inc., Walton, KY
4	Bed Bug Patrol	Clove oil (0.003%), peppermint oil (1%), and sodium lauryl sulfate (1.3%)	Nature's Innovation Inc., Buford, GA
5	Demand CS	λ-Cyhalothrin (9.8%)	Syngenta Crop Protection Inc., Greensboro, NC
6	Ecoexempt IC2	Rosemary oil (10%) and peppermint oil (2%)	EcoSMART Technologies Inc., Franklin, TN
7	EcoRaider	Geraniol (1%), cedar extract (1%), and sodium lauryl sulfate (2%)	Reneotech Inc., North Bergen, NJ
8	Eradicator	Sodium lauryl sulfate (1.5%), sodium chloride (0.5%), and potassium sorbate (0.06%)	Vision Bay LLC, Norcross, GA
9	Essentria	2-Phenethyl propionate (3%), geraniol (2%), rosemary oil (1.5%), and peppermint oil (1.5%)	Envincio LLC, Cary, NC
10	Rest Assured	2-Phenethyl propionate (2%), geraniol (1%), sodium lauryl sulfate (1%), and eugenol (0.3%)	ES & P Global LLC, Miami, FL
11	Green Rest Easy	Cinnamon oil (4%), lemongrass oil (0.3%), clove oil (0.3%), peppermint oil (0.3%), and sodium lauryl sulfate (5%)	RMB Group LLC, Stuart, FL
12	Stop Bugging Me	2-Phenethyl propionate (3%), cinnamon oil (0.1%), eugenol (0.5%), geraniol (0.2%), and sodium lauryl sulfate (0.5%)	Rocasuba Inc., Mashpee, MA
13	Temprid SC	Imidacloprid (21%) and β-cyfluthrin (10.5%)	Bayer Environmental Science, RTP, NC

from the normal registration requirements under FIFRA Section 25b (U.S. Environmental Protection Agency [US EPA] 2014). For consumers, essential oil-based pesticides and detergents are perceived as safer to use. Our preliminary evaluations revealed significant disparities in their efficacy against bed bugs (Singh et al. 2013). To help determine the potential role of natural products in bed bug management, we investigated the efficacy of nine essential oil-based pesticides, two detergent materials, and two conventional insecticides against field-collected bed bug populations. All of them are readily available on the market and commonly used by consumers or professionals.

Materials and Methods

Insects. Two bed bug strains, Indy and Bayonne, were collected during 2008–2009 from infested apartments in Indiana and New Jersey, respectively. The Indy strain and the Bayonne strain were moderately resistant to deltamethrin in our preliminary direct spray bioassay conducted 3 mo before this study. Both strains suffered <40% mortality after direct spray with deltamethrin at the highest label rate (0.06%; Suspend SC; Bayer Environmental Science, Durham, NC). The bed bugs were maintained in plastic containers (4.7 cm in height and 5 cm in diameter) with folded paper as harborages at 26 ± 1°C, 40 ± 10% relative humidity (RH), and a photoperiod of 12:12 (L:D) h, and fed weekly on defibrinated rabbit blood using a Hemotek membrane-feeding system (Discovery Workshops, Accrington, UK). Bugs were starved for 1 wk before bioassays.

Pesticides. Nine essential oil-based pesticides, two detergents, and two synthetic insecticides labeled for bed bugs were evaluated for their efficacy against bed bugs (Table 1). The products were obtained either directly from manufacturers or from commercial distributors. Temprid SC and Demand CS were diluted to 0.15 and 0.03% with water following the label directions. For Ecoexempt IC2, spray solution containing 3.13% Ecoexempt IC2 and 0.78% adjuvant (2,6,8-trimethyl-4-nonyloxy polyethylene oxyethanol; EcoSMART Technologies Inc., Franklin, TN) was prepared using water following the label directions. All other products were ready-to-use sprays.

Direct Spray Bioassay. *Experiment I. Initial Screening.* This experiment was conducted in two separate steps during a 1-mo period to identify the effective products. Two essential oil-based pesticides (Green Rest Easy and Essentria) and two detergent pesticides (Bed Bug 911 and Eradicator) were tested in the first step. In the second step, seven essential oil-based pesticides (Bed Bug Bully, Bed Bug Fix, Bed Bug Patrol, Ecoexempt IC2, EcoRaider, Rest Assured, and Stop Bugging Me), and two synthetic insecticides (Temprid SC and Demand CS) were tested. Twenty Indy strain large nymphs (fourth–fifth instars) were placed on filter paper in each small plastic dish (5.5 cm in diameter and 1.5 cm in height; Fig. 1a). They were sprayed with a pesticide using a Potter spray tower (Burkard Scientific Ltd, Herts, UK) at the application rate of 4.07 mg/cm^2 (1 gal/1000 feet^2). We used this application rate for all pesticides, as it is a standard "point of run off" and allows for fair comparisons among different pesticides. The application rate described in product labels ranged from 0.41 to 1.0 gal/1000 feet^2. Bed bugs in the control group were sprayed with water. Each treatment was replicated three times. Bugs were immediately transferred to clean 1.5-cm-diameter screened plastic petri dishes with a paper harborage after treatment (Fig. 1a). The petri

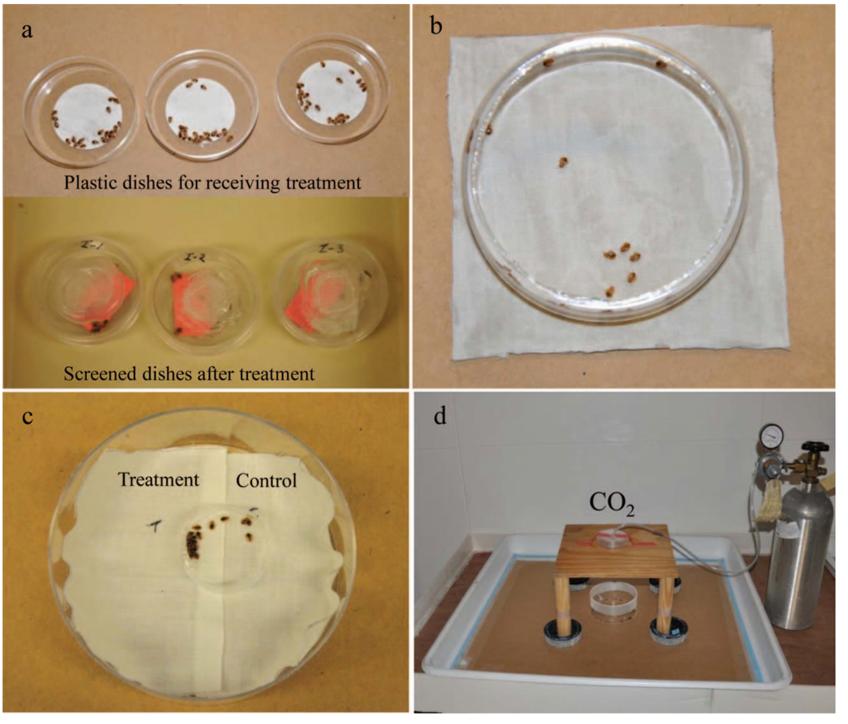

Fig. 1. Experimental setup: (a) Direct spray bioassay, (b) Forced exposure bioassay, (c) Choice exposure bioassay, and (d) Repellency of selected pesticides.

dishes were held in a room at 26°C with 40–50% RH, and a photoperiod of 12:12 (L:D) h. Mortality data were taken at 1, 3, 5, 7, and 10 d after treatment. A bed bug was considered dead if it was not moving or could not right itself when it was prodded with forceps.

Experiment II. Efficacy of Five Essential Oil-Based Pesticides and Two Synthetic Insecticides against a Second Bed Bug Strain. The five most effective essential oil-based pesticides from Experiment I and two synthetic insecticides were tested against Bayonne strain large nymphs to evaluate efficacy against an additional bed bug strain. The products included—EcoRaider, Bed Bug Patrol, Bed Bug Fix, Rest Assured, Bed Bug Bully, Temprid SC, and Demand CS. All treatment procedures were the same as Experiment I.

Experiment III. Efficacy of Five Essential Oil-based Pesticides and Two Synthetic Insecticides against Bed Bug Eggs. Two-day- or 3-d-old Indy strain eggs were taken out from rearing containers. In each replication, 25–30 eggs along with the paper substrate were sprayed following the same procedure as described in Experiment I. Then the eggs along with the paper were transferred to clean 1.5-cm-diameter screened plastic petri dishes. The essential oil-based pesticides and synthetic insecticides used in Experiment II were included. Each treatment was replicated three times. Egg hatching and mortality of the nymphs emerged from eggs were recorded at 5, 7, 10, and 14 d after treatment.

Dry Residue Contact Bioassay. *Limited Forced Exposure to Fresh Residues.* The most effective essential oil-based pesticides (EcoRaider and Bed Bug Patrol) determined in the Direct Spray Bioassay and two synthetic insecticides (Temprid SC and Demand CS) were evaluated against Indy strain large nymphs. The pesticides were applied to 10 cm by 10 cm cardboard panels covered with white 100% cotton fabric at the rate of 4.07 mg/cm^2 using a Potter spray tower. The control panels were sprayed with water. After 1 d, bed bugs were released onto the treated fabric and confined with a plastic ring (9 cm in diameter and 2 cm in height) for 5 min (Fig. 1b). The bugs were then transferred to clean petri dishes following the procedures described in Experiment I. Each treatment was replicated three times. Mortality was recorded at 1, 3, 5, 7, and 10 d after exposure.

Limited Forced Exposure to Aged Residues. Fresh dry residues of EcoRaider were found to be effective in the previous experiment. So this experiment was designed to determine if the aged dry residues of EcoRaider are also effective. Cardboard panels covered with white fabric were treated following the procedures described in previous experiment. Panels were aged for 7 and 14 d in the laboratory at 25°C before exposing them to bed bugs. Each treatment was replicated four times. All other procedures were similar to that in the previous experiment.

Choice Exposure to Fresh Residues. In this bioassay, bed bugs were able to choose to stay on treated or untreated substrate. Two most effective essential oil-based pesticides (EcoRaider and Bed Bug Patrol) and two synthetic insecticides (Temprid SC and Demand CS) were tested. A white 100% cotton fabric square (11.5 cm by 11.5 cm) was cut into two equal halves.

One half was treated with water and the other half was treated with a pesticide using a Potter spray tower. In the control group, both the halves were treated with water. Fabrics were allowed to dry overnight. The two halves were then placed and joined lengthwise in a plastic dish (11.5 cm in diameter and 3.75 cm in height). Twenty Indy strain large nymphs were confined with a plastic ring (3.5 cm in diameter and 1 cm in height) in the center of the dish between the treated and untreated fabric (Fig. 1c). After 2 min, the ring was removed and the bed bugs were allowed to move freely in the dish. Each treatment was replicated three times. Carbon dioxide (CO_2) was released from a 5-lb cylinder (Airgas East Inc., Piscataway, NJ) at 200 ml/min daily for 2 h in the room during early dark cycle to stimulate bed bug foraging behavior. Mortality and location of the bed bugs in each dish was recorded at 1, 3, 5, 7, and 10 d after treatment with the aid of a red light.

Repellency of Essential Oil-Based Pesticides. This experiment was conducted to determine if bed bugs avoid contacting substrates treated with selected essential oil-based pesticides and a synthetic pesticide. EcoRaider, Bed Bug Patrol, and Temprid SC were tested. Paper surgical tape (Caring International, Mundelein, IL) was treated with pesticides using a Potter spray tower at 4.07 mg/cm^2. The control tape was treated with water. After 24 h, the tape was placed on the exterior wall of the black Climbup Insect Interceptors (10 cm in diameter and 2.2 cm in height; Susan McKnight Inc., Memphis, TN). The interior surface of the Climbup interceptors was coated with a light layer of fluoropolymer resin (BioQuip products, Rancho Dominguez, CA) to prevent trapped bed bugs from escaping. Plastic tray arenas (80 by 75 by 5 cm; length by width by height) with a brown paper lined bottom were used (Fig. 1d). A layer of fluoropolymer resin was applied to inner walls of the arenas to prevent the bugs from escaping. A wooden stool (26.5 cm in length and 26.5 cm in width) with four legs was placed in each arena. A filter paper (15 cm in diameter) was placed on the center of each arena below the stool, and then a plastic ring (13.3 cm in diameter and 6.4 cm in height) was placed on the filter paper to confine the bed bugs. A piece of folded cardboard and folded fabric was placed on the filter paper to provide harborages for bed bugs. Four arenas were placed in a nonventilated room with 25 ± 1°C and a photoperiod of 12:12 (L:D) h. Seventy Indy strain bed bugs (35 fourth–fifth instar nymphs and 35 adult males) were confined with a plastic ring. The bugs were acclimated for ≈15 h before the start of the experiment. Each of the four interceptors under each stool had been treated with one of three different pesticides or water (Fig. 1d). At 1 h after the onset of the dark cycle, CO_2 was released from a gas cylinder to the top of stool at 100 ml/min to stimulate bed bug activity. The plastic ring confining the bugs was removed at 1.5 h after dark cycle to initiate the experiment. The numbers of bed bugs trapped in the interceptors and those in the arenas were collected and counted after 4 h with the aid of a red light. Most (80%) of the bugs that were responsive to CO_2 stimulation were trapped in the Climbup interceptors within 4 h in our preliminary assays.

Statistical Analysis. The Abbott (1925) formula was used to calculate corrected mortality. Percentage corrected mortality, percentage egg hatch and survival, and percent trap catch values were arcsine square root transformed to meet the assumptions of normality and homogeneity of variances. The repeated-measures analysis of the mortality data was done using Mixed model (JMP 2014) to determine differences between treatments and their interaction with time. Each source of variation, between and within treatments (Day and Treatment × Day) was included as an effect in the model. Replicate was included as random effect. One-way analysis of variance was used when only one observation period was selected to compare the treatments. When the interactions were significant, Tukey's HSD (α = 0.05) was used to separate the means. All analyses were performed with JMP version 11 (SAS Institute 2012).

Results

Direct Spray. *Experiment I. Initial Screening.* There were significant differences in bed bug mortality among pesticides at 10 d after treatment (F = 25.4; df = 12, 24; P = 0.0001). Mortality by EcoRaider (100.0 ± 0.0%) and Bed Bug Patrol (92.0 ± 6.0%) was statistically higher than those by other essential oil-based pesticides tested; however, both of them were not significantly different from Temprid SC (100.0 ± 0.0%; Fig. 2). Demand CS (78.0 ± 4.4%) was less effective than EcoRaider and Temprid SC. Most essential oil-based pesticides and detergents including Essentria, Green Rest Easy, Eradicator, Bed Bug 911, Stop Bugging Me, and Ecoexempt IC2 caused 0–30% mortality. The mortality in the untreated control was <10%.

Experiment II. Efficacy Against a Second Bed Bug Strain. Significant differences in bed bug mortality were observed among pesticides (F = 10.2; df = 12, 28; P = 0.0001). At 1 d, Temprid SC (100.0 ± 0.0%) caused significantly higher mortality than all other pesticides (Fig. 3). Among the essential oil-based pesticides, EcoRaider (82.0 ± 4.4%) caused significantly higher mortality than other pesticides. At 5 d, Temprid SC (100.0 ± 0.0%) and EcoRaider (87.8 ± 1.7%) were statistically similar; however, EcoRaider caused significantly higher mortality than all other essential oil-based pesticides except Bed Bug Patrol (75.8 ± 1.7%), which caused similar level of mortality. At 10 d, Temprid SC (100.0 ± 0.0%), EcoRaider (100.0 ± 0.0%), Bed Bug Patrol (98.2 ± 1.8%), and Bed Bug Bully (92.7 ± 3.6%) caused similar high mortality. Temprid SC and EcoRaider were statistically different from Bed Bug Fix, Demand CS, and Rest Assured. The mortality in the untreated control after 10 d was 8.3 ± 4.4%.

Experiment III. Efficacy against Eggs. Among the five tested essential oil-based pesticides, only EcoRaider caused high-level egg mortality at 14 d (86.7 ±

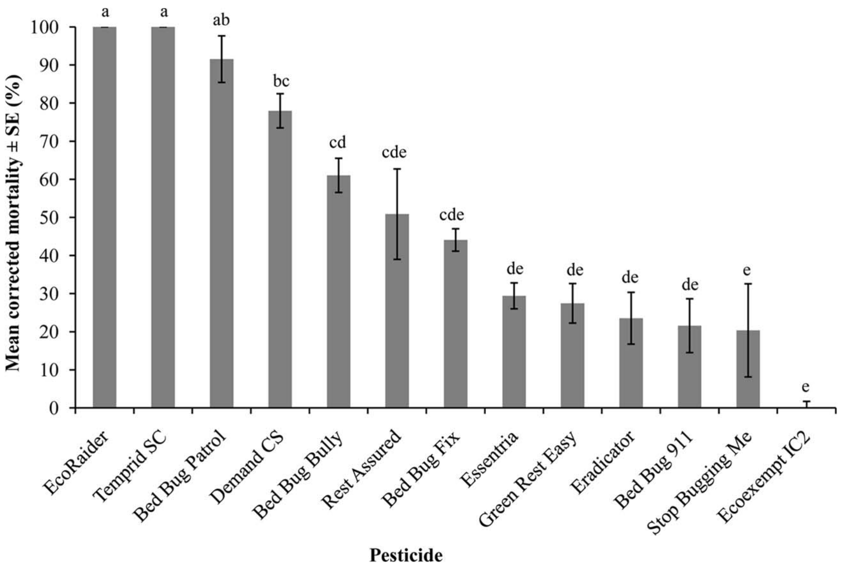

Fig. 2. Efficacy of essential oil-based pesticides and synthetic insecticides against Indy strain nymphs in a direct spray bioassay at 10 d after treatment. Analysis was based on arcsine square root transformed data, but actual mean values are presented here. Means with the different letters are statistically different ($P < 0.05$, Tukey's HSD test).

1.1%) after treatment (Fig. 4). All other pesticides caused <17% egg mortality ($F = 20.8$; df = 6, 14; $P = 0.0001$). EcoRaider was significantly more effective than Temprid SC (58.0 ± 5.0%) and Demand CS (67.4 ± 0.5%). The nymphs hatched from eggs treated by EcoRaider, Temprid SC, and Demand CS suffered significantly higher mortality than those from eggs treated by the other four essential oil-based pesticides ($F = 12.3$; df = 6, 17; $P = 0.0003$). The mean percent egg hatch and survival of nymphs in control group after 14 d was 97.5 ± 0.04% and 98.2 ± 0.8%, respectively.

Dry Residue Contact Bioassay. *Limited Forced Exposure to Fresh Residues.* The four pesticides were significantly different in their residual efficacy ($F = 16.1$; df = 6, 16; $P = 0.0001$; Fig. 5). At 1 d, Temprid SC (63.3 ± 6.0%) caused significantly higher mortality than that by EcoRaider (11.6 ± 6.6%) and Bed Bug Patrol (3.3 ± 3.3%). At 10 d, no significant difference was observed in mortality among Temprid SC, EcoRaider, and Bed Bug Patrol. The mean mortality by Temprid SC, EcoRaider, and Bed Bug Patrol was 100.0 ± 0.0, 93.3 ± 6.6, and 93.3 ± 6.6%, respectively. There was no mortality in the untreated control. Temprid SC produced significantly higher mortality than Demand CS at 5 and 10 d after treatment.

Limited Forced Exposure to Aged Residues. Both 7 and 14 d aged dry residues of EcoRaider produced similar level of mortality at 1, 5, and 10 d after exposure ($F = 1.8$; df = 2, 12; $P = 0.2$). The mean bed bug

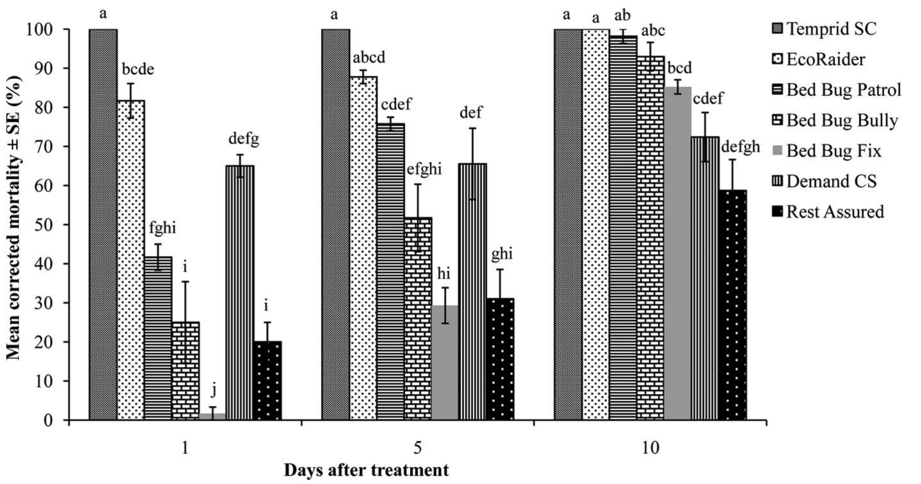

Fig. 3. Efficacy of selected essential oil-based pesticides and synthetic insecticides against Bayonne strain nymphs in a direct spray bioassay. Analysis was based on arcsine square root transformed data, but actual mean values are presented here. Means with the different letters are statistically different ($P < 0.05$, Tukey's HSD test).

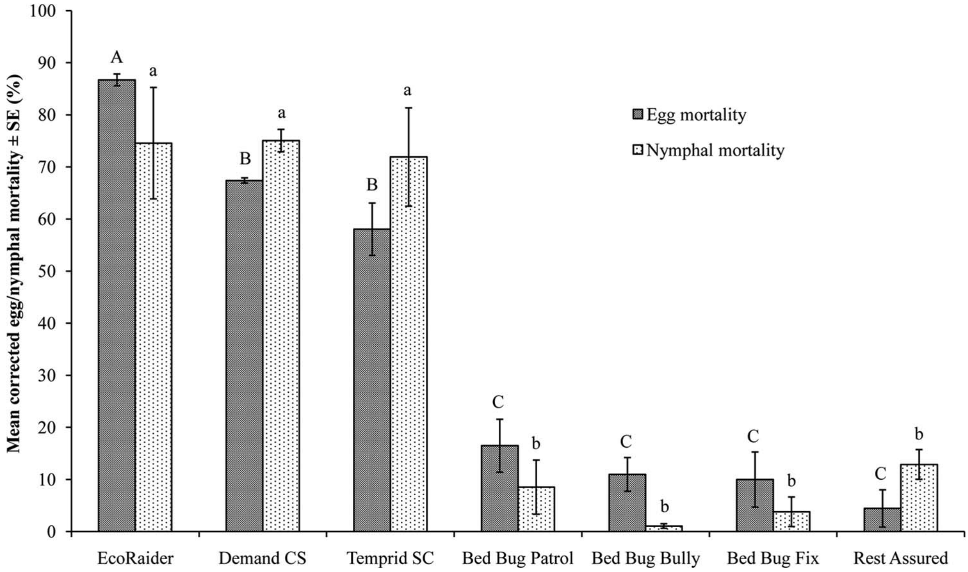

Fig. 4. Mortality of essential oil-based pesticide- and synthetic insecticide-treated eggs and nymphs hatched from treated eggs at 14 d after treatment. Analysis was based on arcsine square root transformed data, but actual mean values are presented here. Bars with different letters of the same case are significantly different ($P < 0.05$, Tukey's HSD test).

mortality caused by 7 and 14 d aged residues of EcoRaider was 92.5 ± 4.3 and 90.0 ± 2.0% at 10 d after exposure, respectively. There was no mortality in the untreated control.

Choice Exposure to Fresh Residues. The pesticides tested were significantly different in their residual efficacy ($F = 5.0$; df = 6, 16; $P = 0.004$). Temprid SC caused significantly higher mortality than Demand CS at 1, 5, and 10 d after treatment. Temprid SC and Demand CS were significantly more effective than EcoRaider and Bed Bug Patrol. At 10 d, the mean bed bug mortality by Temprid SC, Demand CS, Bed Bug Patrol, and EcoRaider was 90.0 ± 2.9, 56.7 ± 4.8, 10.0 ± 2.9, and 1.7 ± 1.7%, respectively (Fig. 6). There was no mortality in the untreated control after 10 d.

Repellency of Essential Oil-Based Pesticides. The mean number of bed bugs trapped in interceptors covered with Temprid SC-, Bed Bug Patrol-, EcoRaider-, and water-treated tape were 28.1 ± 4.2, 35.2 ± 8.0, 21.4 ± 7.4, and 15.4 ± 1.4%, respectively. They were not significantly different ($F = 2.0$; df = 3, 12; $P = 0.15$).

Discussion

This is the first comprehensive study evaluating the efficacy of essential oil-based pesticides and detergent

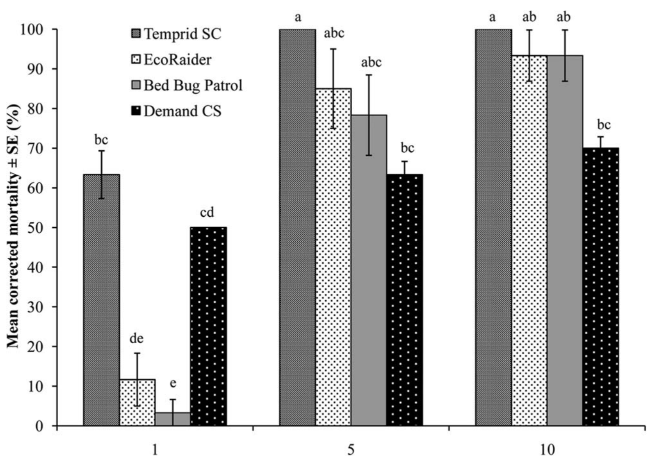

Fig. 5. Efficacy of fresh dry residues of essential oil-based pesticides and synthetic insecticides against Indy strain nymphs in limited forced exposure bioassay. Analysis was based on arcsine square root transformed data, but actual mean values are presented here. Means with the different letters are statistically different ($P < 0.05$, Tukey's HSD test).

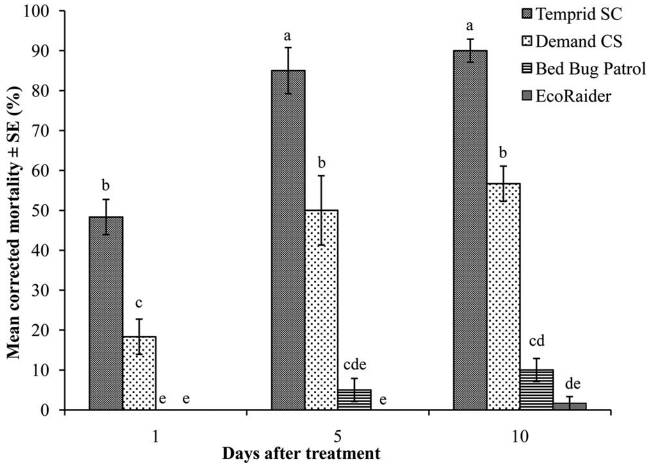

Fig. 6. Efficacy of essential oil-based pesticides and synthetic insecticides against Indy strain nymphs in choice exposure bioassay. Analysis was based on arcsine square root transformed data, but actual mean values are presented here. Means with the different letters are statistically different ($P < 0.05$, Tukey's HSD test).

products labeled for bed bug control. Most of the evaluated natural insecticides failed to cause high mortality (i.e., > 80%) to bed bugs as a direct spray. Nevertheless, EcoRaider and Bed Bug Patrol showed promise as a direct spray for controlling mobile stages of bed bugs; however, the speed of kill is much slower than the synthetic insecticide (Temprid SC). Only one of the tested essential oil-based products (EcoRaider) caused high egg mortality. EcoRaider was more effective than Demand CS, a commonly used pyrethroid insecticide. The moderate level of mortality caused by Demand CS is mostly likely due to pyrethroid resistance in the bed bugs. EcoRaider aged dry residue on fabric surface maintained high insecticidal activity at 14 d. Although EcoRaider and Bed Bug Patrol were effective in direct spray and forced exposure bioassays (fresh and aged residues), they were ineffective in choice exposure bioassay. Bed bugs seemed to avoid staying on substrates treated with essential oil-based pesticides in the absence of host cues. However, when a host cue (CO_2) was present, bed bugs did not exhibit significant avoidance behavior, implying that these products are not effective repellents for bed bugs. Therefore, essential oil-based pesticides may be useful as a direct spray. It is also possible that these products would be effective as a residual spray if applied directly to bed bug harborage sites where aggregation cues exist; however, additional studies are required to investigate this.

The listed active ingredients in EcoRaider and Bed Bug Patrol have been shown to have toxic effect against many insect pests. Eugenol at the rates of 0.148 ml/cm^2, 0.003 ml/43.0 cm^2, and 10 μl/g exhibited toxic activity against the American cockroach (Ngoh et al. 1998), yellowfever mosquito, *Aedes aegypti* L. (Bhatnagar et al. 1993), and the Formosan subterranean termite, *Coptotermes formosanus* Shiraki (Cornelius et al. 1997), respectively. In a separate laboratory direct spray bioassay, a water solution containing 10% cedar oil and 0.78% adjuvant (2,6,8-trimethyl-4-nonyloxy polyethylene oxyethanol) caused only 22.2 ± 4.4% mortality to a field strain (N. S., unpublished data). The concentrations of essential oils in EcoRaider and Bed Bug Patrol are very low and are unlikely to be lethal to bed bugs when used alone. Some of the active ingredients in these two products also appeared in other products (Bed Bug Fix, Green Rest Easy, and Essentria) that exhibited very low efficacy. Other factors besides the active ingredients must have accounted for the high efficacy of some essential oil-based pesticides. Adjuvants such as wetting agents, spreaders, stabilizers, defoamers, stickers, and solvents may produce synergistic effects to essential oils by improving penetration through insect cuticle and translocation of the active ingredients within insect body.

The efficacy of any pesticide can vary with the testing method, rate of application, strain, life stage of bed bugs, and physiological state of bed bugs. We used a Potter spray tower to standardize the application rate to make fair comparisons of various products. The Potter spray tower delivers much more uniform and fine droplets on the treated substrates compared with the accuracy of trigger spray bottles provided by the manufacturers. In addition, the application rate (1 gal/1,000 feet^2) used in all experiments is equal or higher than the label rates of the natural pesticides tested: Stop Bugging Me—0.53, Bed Bug Fix—0.41, Rest Assured—0.41, and Bed Bug Bully—1.0 gal/1,000 feet^2. It is reasonable to believe that when following the product label directions, these products will likely result in lower efficacy than that reported in this study.

In summary, our study demonstrated the disparities in efficacy among various natural products and the effect of testing conditions on product efficacy. Two essential oil-based bed bug control products showed high efficacy as a direct spray. The results were obtained under ideal conditions where each bed bug was directly sprayed or exposed to the treatments. Under field conditions, bed bugs hide in cracks, crevices, creases, and many other places where insecticide application may not be directly applied onto the hidden insects. Additional studies under field conditions are warranted to determine the field efficacy of Eco-Raider and Bed Bug Patrol and how they can be incorporated into a bed bug management program.

Acknowledgments

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