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Household and Structural Insects

Common consumer residual insecticides lack efficacy against insecticide-susceptible and resistant populations of the German cockroach (Blattodea: Ectobiidae)

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The German cockroach, *Blattella germanica* (L.) (Blattodea: Ectobiidae), is a ubiquitous pest in affordable housing. They represent a major threat to human health due to their contribution of asthma-exacerbating allergens and the potential to transfer pathogenic microorganisms indoors. Despite well-documented pyrethroid resistance, pyrethroid-based broadcast residual insecticide products are often used by residents to control cockroaches in their homes. Additionally, there is little empirical independent testing of these products. Thus, it remains unclear how effective these commonly used do-it-yourself products are at controlling German cockroaches. This study represents a comprehensive examination of the efficacy of these products with direct, limited, and continuous exposure assays on a variety of common household surfaces on field populations of cockroaches with varying levels of pyrethroid resistance. While most products performed well when applied directly to test insects, mortality was substantially lower across all surfaces with limited exposure (30 min). In continuous exposure assays on a nonporous surface, products took at least 24 hr to cause 100% mortality in a field population, with some products taking up to 5 d to achieve 100% mortality. The findings of this study demonstrate a lack of residual efficacy from common pyrethroid-based consumer-use pesticides products. Given that it is not feasible to find and treat every cockroach in a home directly, the residuality of spray-based formulations is critical for products designed to control German cockroaches. Without residual efficacy, as shown in the consumer aerosol and spray products tested, we expect these products to add little to no value to cockroach control.

Key words: pyrethroids, do-it-yourself pest control, topical applications, aerosol insecticides

Introduction

The German cockroach, *Blattella germanica* (L.), is a widely distributed synanthropic pest, infesting human structures around the world (Schal and Hamilton 1990, Rust et al. 1995, Tang et al. 2019, Wang et al. 2021). Infestations present a particular pest control challenge in affordable multifamily housing, where building structure and an abundance of resources can sustain populations and make eradication difficult (Miller et al. 2021).

Infestations of cockroaches present a risk to human health, introducing allergens into the environment that can act as core asthma triggers and induce asthma response in individuals with allergic asthma (Bernton and Brown 1964). The National Cooperative Inner City Asthma Study has documented a strong correlation between exposure to cockroach allergens, individual sensitization, and asthma morbidity (Rosenstreich et al. 1997, Gruchalla et al. 2005), which suggests that prolonged cockroach infestations carry a substantial risk of negative health consequences. While allergens have been identified from both American cockroaches, *Periplaneta americana* (L.), and *B. germanica*, the former is considered a peridomestic species, while German cockroaches are solely found inside of human structures and thus are the primary focus of cockroach allergen concerns (Gore and Schal 2007). Furthermore, the low quantities of certain allergens that are required for an individual to become sensitized (i.e., 0.2 µg of the allergen Bla g 1 per gram of dust; Eggleston et al. 1998) enhances the threat of negative health risks posed by these household pests. Source reduction in the form of population control is critical to allergen mitigation and cockroach elimination using baits resulting in allergen reduction has been demonstrated in the literature (Arbes et al. 2004, Sever et al. 2007, Kass et al. 2009). Therefore, the identification of effective control strategies is critical to mitigate these health risks.

In addition to health concerns, cockroach infestations are often accompanied by feelings of hopelessness that cockroach problems will ever be resolved. Surveys of public housing across the Mid-Atlantic found concern among residents about negative impacts of cockroaches, as well as skepticism that cockroaches could be eliminated within their homes (Wood et al. 1981). To combat pest problems, pesticide use in low-income multifamily housing tends to be high (Landrigan et al. 1999, Surgan 2002). However, low-bid pest control contracts are often awarded in affordable housing, which fail to rectify pest issues in the long term (Wang et al. 2019a, Miller et al. 2021).

A lack of effective cockroach control programs in housing can drive residents to purchase products and attempt to control cockroaches in their homes on their own (Wood et al. 1981, Davies and Petranovic 1986). Spray insecticide products marketed to consumers are available at many retail establishments. Multiple studies have demonstrated not only the commonality of pesticide usage within the home (Davis et al. 1992, Adgate et al. 2000, Bass et al. 2001) but also the likelihood that pesticide use by residents may be even higher than what is reported in national surveys (Adgate et al. 2000). Despite their ready availability and widespread use, do-it-yourself (DIY) pest control products maintain a poor reputation. This is likely due to reports of product misuse and treatment failures. For example, total-release foggers are completely ineffective at controlling both bed bugs (Jones and Bryant 2012) and German cockroaches (DeVries et al. 2019a). Furthermore, their use leads to contamination of indoor surfaces with pesticides, leading to extensive exposure risk (C.D.C 2008, Keenan et al. 2009, DeVries et al. 2019a, Wang et al. 2019c). Given the documented inefficacy and exposure risks of total-release foggers, it is critical to evaluate other DIY products, particularly spray and aerosol formulations that pose a high risk of contaminating indoor surfaces with pesticide residues.

Pyrethroid-based liquid/aerosol formulations are often purchased and used within the home (Spitzer 2002, Bekarian et al. 2006, Wang et al. 2019b). However, little data exists on the efficacy of these products. Conspicuously, many of these spray formulations contain pyrethroids as the active ingredient, with a 2011 New York City survey of pest control products confirming pyrethroids as the most common active ingredient in nonprofessional pest control spray products (Horton et al. 2011). In the past 20 yr, pyrethroids have come to occupy a greater portion of the residential insecticide market, likely due to a shift away from actives such as organophosphates (Horton et al. 2011). In the past 35 yr, significant pyrethroid resistance in German cockroaches has been well documented (Cochran 1989, Atkinson et al. 1991, Wei et al. 2001, Chai and Lee 2010, Wu and Appel 2017, DeVries et al. 2019b, Fardisi et al. 2019, Lee et al. 2022), which calls into question not only their efficacy, but also how long treatments on surfaces remain effective against German cockroaches. Thus, there is a need for an independent examination of these products and how effective they might be at controlling cockroaches within the home. In the present study, we tested common consumer-grade pyrethroid-based spray and aerosol products for their efficacy when directly applied to German cockroaches, as well as for their residual efficacy on a variety of common household surfaces with limited and continuous exposure assays. These findings are discussed in relation to the continued use of these products for German cockroach control.

Materials and Methods

Study Insects

Four laboratory-reared German cockroach populations were used to examine DIY spray-based products for efficacy. Orlando Normal (ON) is an insecticide-susceptible population that has been reared in the laboratory without exposure to any insecticides for more than 70 yr and has been used in a number of recent insecticide toxicity studies (Wu and Appel 2017, DeVries et al. 2019b, Oladipupo et al. 2020). CC29 and VS101 represent field-collected German cockroach populations collected in Raleigh, NC between 2018 and 2019 (González-Morales et al. 2022) and CTHR is a German cockroach population collected in Lexington, KY in 2021. Colonies of all populations were reared in 3.8-L glass jars (Arkansas Glass Container Corp., Jonesboro, Arkansas, USA) at ~28 °C, 40%–55% RH. All study insects were reared under a 12:12 (L:D) photoperiod and provided rolled corrugated cardboard as harborage, food (Mazuri Rat & Mouse Diet, PMI Nutrition International, Arden Hills, Minnesota, USA), and water.

Study Conditions

All assays took place under laboratory conditions: ~28 °C, 40%–55% RH, 12:12 (L:D) photoperiod.

Topical Applications

Topical applications were conducted to determine the lethal dose of cypermethrin (pyrethroid representative for consumer aerosol/spray products) necessary to kill 50% (LD_{50}) of cockroaches, following the methodology of DeVries et al. (2019b). Groups of 10 adult males from the ON, CC29, VS101, and CTHR populations were briefly anesthetized with CO_2 and a 50-µL repeating dispenser syringe (size: 50 µL; Hamilton Company, Reno, Nevada, USA) was used to apply 1 µL of acetone containing each insecticide to the metathorax between the coxae of each cockroach. Insecticide dilutions ranged from acetone-only controls (0 ng) to 50 µg (cypermethrin, >90% purity; Sigma-Aldrich, St. Louis, Missouri, USA). Seven concentrations of cypermethrin in acetone (0.010, 0.020, 0.050, 0.075, 0.100, 0.150, and 0.200 µg/µL) were used to create dose–response curves for the susceptible ON population and 5 concentrations were used to plot dose–response curves for the field-collected populations: CC29 (0.5, 1, 2, 5, and 10 µg/µL), VS101 (0.5, 1, 2, 5, and 10 µg/µL), CTHR (2, 5, 10, 20, and 50 µg/µL). Treated cockroaches were placed in clean plastic Petri dishes and provided food (rat chow) and water. Mortality was assessed at 24 hr, based on DeVries et al. (2019b) and cockroaches that did not respond to stimulus were considered dead.

Residual Spray Insecticides

Four consumer-grade residual insecticides marketed for cockroach control were tested within our study, including 2 aerosol formulations—Raid Ant and Roach Killer 26, Outdoor Fragrance Free (imiprothrin 0.060%, cypermethrin 0.100%, aerosol spray, SC Johnson, Inc., Racine, Wisconsin, USA) and Hot Shot Roach, Ant and Spider Killer (imiprothrin 0.075%, lambda-cyhalothrin 0.025%, aerosol spray, United Industries Corporation, St. Louis, Missouri, USA), and 2 liquid formulations—Ortho Home Defense Insect Killer for Indoor & Perimeter (bifenthrin 0.05%, zeta-cypermethrin 0.0125%, liquid spray, The Ortho Home Defense Group, Maysville, Ohio, USA), and Spectracide Bug Stop Home Barrier (gamma-cyhalothrin 0.025%, liquid spray, United Industries Corporation).

Direct Contact

Direct contact assays were conducted in small plastic cups (Choice 16oz. Ultra Clear PET plastic round deli container, UPC

Code:400011856465, webstaurantstore.com, USA) greased with petroleum jelly (Equate petroleum jelly, Walmart, Inc., Bentonville, Arkansas, USA) to prevent insect escape. Adult male cockroaches ($n = 10$) were lightly anesthetized with carbon dioxide (CO_2) to facilitate handling. Each product was applied using its own delivery system as a 1-s spray to ensure all cockroaches were sufficiently coated in the product. Product delivery rates were calculated as follows: HotShot Roach, Ant and Spider Killer, 0.87 g/s; Raid Ant and Roach Killer, 0.57 g/s; Ortho Home Defense Insect Killer, 1.24 g/s; and Spectracide Bug Stop Home Barrier, 0.99 g/s. All cockroaches were allowed to recover from CO_2 exposure before being treated directly with one of the liquid/aerosol pyrethroid products. Immediately (<30 s) after direct application, treated insects were transferred to a clean plastic cup (16 oz) pregreased with petroleum jelly containing food, water, and harborage. Cups were covered with mesh to allow for air flow but to prevent escape. No-treatment controls were treated with deionized water (DI H_2O) using an aerosol spray bottle (100 mL, Nalgene aerosol spray bottle, manufacturing number: 2430-0200, Thermo Scientific, Waltham, Massachusetts, USA). Mortality was evaluated at 24 hr and cockroaches that were nonresponsive to stimulus were considered dead. For each product–population combination 6 replicates were performed.

Limited Exposure

Limited exposure assays were conducted on 3 household surfaces commonly found in a residential kitchen: painted drywall (CertainTeed, Malvern, Pennsylvania, USA), ceramic tile (Sovereign Stone, StonePeak Ceramics, Crossville, Tennessee, USA), and 1-mm thick 430 stainless steel (McMaster-Carr, Elmhurst, Illinois, USA). Painted drywall was prepared by applying 2 light coats of Latex Interior Paint + Primer (Model #IN4021001-16, HGTV HOME Infinity Flat Ultra White Tintable, The Sherwin-Williams Co., Cleveland, Ohio, USA) using a roller to drywall (CertainTeed). The paint was allowed to dry 4 hr between coats of paint and allowed to dry for 1 wk before limited exposure assays were run. Painted drywall represented a porous surface and ceramic tile and stainless steel represented a nonporous surface, in line with product performance testing guidelines (EPA 2019). Sections (15.24 cm × 30.48 cm) of each substrate were treated with one of the 4 residual spray products as a 2-s spray to the surface from ~61 cm away under a fume hood until the surface was completely wetted by the application but not to run off. The treated substrates were allowed to dry under ambient room conditions (23 °C, 45% RH) for 12 hr. Substrates were confirmed to be dry prior to the introduction of cockroaches. Male German cockroaches ($n = 10$) were introduced onto the substrate and forced to remain in contact with treated substrates for 30 min using an inverted plastic cup greased with petroleum jelly (exposure surface = 89.92 cm^2). After 30 min, cockroaches were transferred to a clean plastic cup (16 oz) pregreased with petroleum jelly containing food, water, and harborage, and mortality was recorded after 24 hr. For each experimental unit (product, population, exposure method, etc.), 3–6 replicates were performed.

Continuous Exposure

To assess the efficacy of products under the ideal conditions of continuous exposure and a nonporous surface, ceramic tile substrates were treated with one of the 4 liquid/aerosol products using the same methods as in the limited exposure assays, and allowed to dry for 24 hr before cockroach introduction (as described in *Limited Exposure* above). Cockroaches ($n = 10$) from one representative field-collected cockroach population (CTHR) were forced to remain in contact with a treated surface using inverted petroleum jelly-greased plastic cups (exposure surface = 89.92 cm^2). Study insects in continuous exposure assays were not provided food or water to ensure that the only surface they could be in contact with was the treated surface. Mortality was recorded at 15 and 30 min, 1, 2, 4, 8, 24, 48, 72, 96, and 120 hr, or until all insects were dead. Three replicates of each product were performed.

Statistical Analyses

The dose required to kill 50% of insects (LD_{50}) was determined using Probit analysis. Resistance ratios for each field-collected population were calculated by dividing the LD_{50} of each field population by the LD_{50} of the ON susceptible population.

For direct exposure assays, there was no mortality at 24 hr in any DI H_2O-treated control insects. As such, no corrections for control mortality were done for direct exposure data. Due to the binomial distribution and non-normality of the direct exposure data, and in order to compare it to the EPA product performance threshold of 90%, population–product combinations were evaluated for mortality that exceeded 90%, as determined by nonoverlap of 95% confidence intervals (CIs), calculated from linear regressions of each product–population combination. That is, we considered each product–population combination a "YES" or a "NO" for meeting/exceeding the 90% mortality threshold based on the nonoverlap of the lower 95% CI with 90. Given the specific value we wanted to compare our data to, we were unable to use a Kruskal–Wallis Test, which compares ranks alone, or a Chi-squared test, which only compares proportions.

Control mortality was <2% for all replicates on all surfaces in limited exposure assays. As such, no data corrections were run. Impacts of limited exposure to consumer-grade cockroach spray product residues on mortality for the 4 German cockroach populations on the 3 common household surfaces were analyzed for within-surface differences using Kruskal–Wallis tests. Dunn's test was used to generate pairwise comparisons between products.

The impacts of continuous exposure to surfaces treated with consumer-grade spray products on survivorship were analyzed with Kaplan–Meier survival analysis (Kaplan and Meier 1958). Log-rank tests were used to compare survivorship curves between products and no-treatment controls.

All analyses were conducted in R version 2023.09.0 + 463 (R Development Core Team 2023) or JMP Pro 17 (JMP Statistical Discovery LLC, Cary, NC, USA), and visualizations were created in R using the ggplot2 package (v3.4.3; Wickham 2016).

Results

Topical Applications

All field populations (CC29, VS101, and CTHR) evaluated displayed high resistance to cypermethrin compared to the laboratory-susceptible population (Table 1). CTHR had the highest resistance ratio compared to the ON population of 358-fold. CC29 and VS101 had resistance ratios of 68.78 and 84.37, respectively, suggesting resistance levels that fall between those of the ON and CTHR populations.

Direct Exposure

There was 100% mortality for all German cockroach populations when directly sprayed with Spectracide Bug Stop and between 98% and 100% mortality for all cockroach populations when cockroaches were directly sprayed with Raid Ant and Roach

Killer. Ortho Home Defense had mixed efficacy with direct application (Table 2) with mean percent mortality of 33.8 (CC29), 77.4% (CTHR), 66.6% (VS101), and 100.0% (ON). Hot Shot Ant, Roach, and Spider Killer also had mixed efficacy with mean percent mortality of 3.9% (CTHR), 96.8% (CC29), 100.0% (VS101), and 100.0% (ON; Table 2). There was 100% mortality across all replicates for ON across all products and for VS101, CTHR, and CC29 treated with Spectracide Bug Stop. All product–population combinations had greater or equal to 90% mortality based on nonoverlap of the lower 95% CI, except for the following: Hot Shot-CTHR, Ortho Home Defense-CC29, Ortho Home Defense-VS101, Ortho Home Defense-CTHR (Table 2).

Limited Exposure

There was <2% mortality across all limited exposure controls at 24 hr, with all but 2 replicates having no mortality. Regardless of population or product, surface type had a significant impact on mortality ($\chi^2 = 33.7522$, df = 2, $P \leq 0.001$), with comparable mortality on ceramic and stainless steel but both surfaces resulting in much greater mortality compared to painted drywall. Mortality in the susceptible population differed significantly from field populations across all products on ceramic tile and stainless steel (Hot Shot Roach, Ant and Spider Killer-Ceramic: $\chi^2 = 15.47$, df = 3, $P = 0.001$; Hot Shot Roach, Ant and Spider Killer-Stainless Steel: $\chi^2 = 11.14$, df = 3, $P = 0.011$; Raid Ant and Roach Killer-Ceramic: $\chi^2 = 17.32$, df = 3, $P < 0.001$, Raid Ant and Roach Killer-Stainless Steel: $\chi^2 = 12.09$, df = 3, $P = 0.007$; Ortho Home Defense-Ceramic: $\chi^2 = 14.86$, df = 3, $P = 0.002$; Ortho Home Defense-Stainless Steel: $\chi^2 = 12.44$, df = 3, $P = 0.006$; Spectracide Bug Stop-Ceramic: $\chi^2 = 15.39$, df = 3, $P = 0.002$; Spectracide Bug Stop-Stainless Steel: $\chi^2 = 10.95$, df = 3, $P = 0.012$; Fig. 1). The susceptible population had significantly higher mortality than field populations on painted drywall treated with Spectracide Bug Stop ($\chi^2 = 8.03$, df = 3, $P = 0.045$), but susceptible population mortality did not differ from field-collected populations on painted drywall treated with Hot Shot Roach, Ant and Spider Killer, Ortho Home Defense, or Raid Ant and Roach Killer ($P > 0.05$). Average mortality for all field populations by product by surface combinations did not exceed 20% at 24 hr. Additionally, mortality did not exceed 50% in any replicate of field populations.

Continuous Exposure

With continuous exposure of field-collected cockroaches (CTHR) to products on ceramic tile, survival probability was significantly higher on untreated tile (control) than on all treated tiles ($\chi^2 = 112$, df = 4, $P < 0.001$). Survival probability did not differ between Raid Ant and Roach Killer and Ortho Home Defense Home Defense and survival probability did not differ between Hot Shot Roach, Ant and Spider Killer and Spectracide Bug Stop. While Raid Ant and Roach Killer and Ortho Home Defense did not significantly differ from one

Table 1. Toxicity of topically applied cypermethrin to several populations of the German cockroach

Population[a]	*n*	LD_{50} (μg/male cockroach)	LD_{50} 95% CI	Slope ± SE	χ2 (df)	RR[b]
Orlando Normal	211	0.045	0.037–0.053	3.09 ± 0.34	10.1 (5)	—
CC29	150	3.098	2.447–3.974	2.49 ± 0.33	2.0 (3)	68.8
VS101	150	3.800	2.906–5.196	2.07 ± 0.29	5.6 (3)	84.4
CTHR	150	16.135	10.458–28.957	1.13 ± 0.24	2.6 (3)	358.2

[a]Orlando Normal represents an insecticide-susceptible *Blattella germanica* laboratory population. CC29 and VS101 were collected from apartments Raleigh, North Carolina between 2018 and 2019 (González-Morales et al. 2022). CTHR was collected from a home in Lexington, Kentucky in 2021.
[b]Resistance ratios (RR) were calculated by dividing LD_{50} for each field population by LD_{50} for Orlando Normal (susceptible).

Table 2. Impacts of direct exposure with consumer-grade cockroach aerosol/liquid products on percent mortality at 24 hr for 4 German cockroach populations

Treatment	Population	Average percent mortality (*n* = 6)	Mortality 95% CI	Median percent mortality (*n* = 6)	Range of percent Mortality (*n* = 6)	Mortality > 90% (YES/NO)[a]
Raid Ant and Roach Killer (active ingredients: imiprothrin, 0.060%; cypermethrin, 0.100%)	CC29	98.5%	(94.6–102.4)	100.0%	90.9%–100.0%	YES
	VS101	98.3%	(94.1–102.6)	100.0%	90.0%–100.0%	YES
	CTHR	98.5%	(94.6–102.4)	100.0%	90.9%–100.0%	YES
	ON (susceptible)	100.0%	(100.0–100.0)	100.0%	100.0% to 100.0%	YES
Hot Shot Roach, Ant and Spider Killer (active ingredients: imiprothrin, 0.075%; lambda-cyhalothrin, 0.025%)	CC29	96.8%	(91.6–102.0)	100.0%	90.9%–100.0%	YES
	VS101	98.3%	(94.2–102.6)	100.0%	90.0–100.0%	YES
	CTHR	3.9%	(0.0–10.4)	0.0%	0.0%–12.50%	NO
	ON (susceptible)	100.0%	(100.0–100.0)	100.0%	100.0%–100.0%	YES
Ortho Home Defense (active ingredients: bifenthrin, 0.0500%; zeta-cypermethrin, 0.0125%)	CC29	33.8%	(21.7–45.9)	30.0%	20.0%–100.0%	NO
	VS101	66.6%	(43.0–90.3)	70.0%	40.0%–100.0%	NO
	CTHR	77.4%	(51.4–103.3)	83.3%	37.5%–100.0%	NO
	ON (susceptible)	100.0%	(100.0–100.0)	100.0%	100.0%–100.0%	YES
Spectracide Bug Stop (active ingredient: gamma-cyhalothrin, 0.025%)	CC29	100.0%	(100.0–100.0)	100.0%	100.0%–100.0%	YES
	VS101	100.0%	(100.0–100.0)	100.0%	100.0%–100.0%	YES
	CTHR	100.0%	(100.0–100.0)	100.0%	100.0%–100.0%	YES
	ON (susceptible)	100.0%	(100.0–100.0)	100.0%	100.0%–100.0%	YES

Mortality 95% Confidence Intervals (CIs) provided within parentheses.
[a]Based on lower confidence interval less than 90.

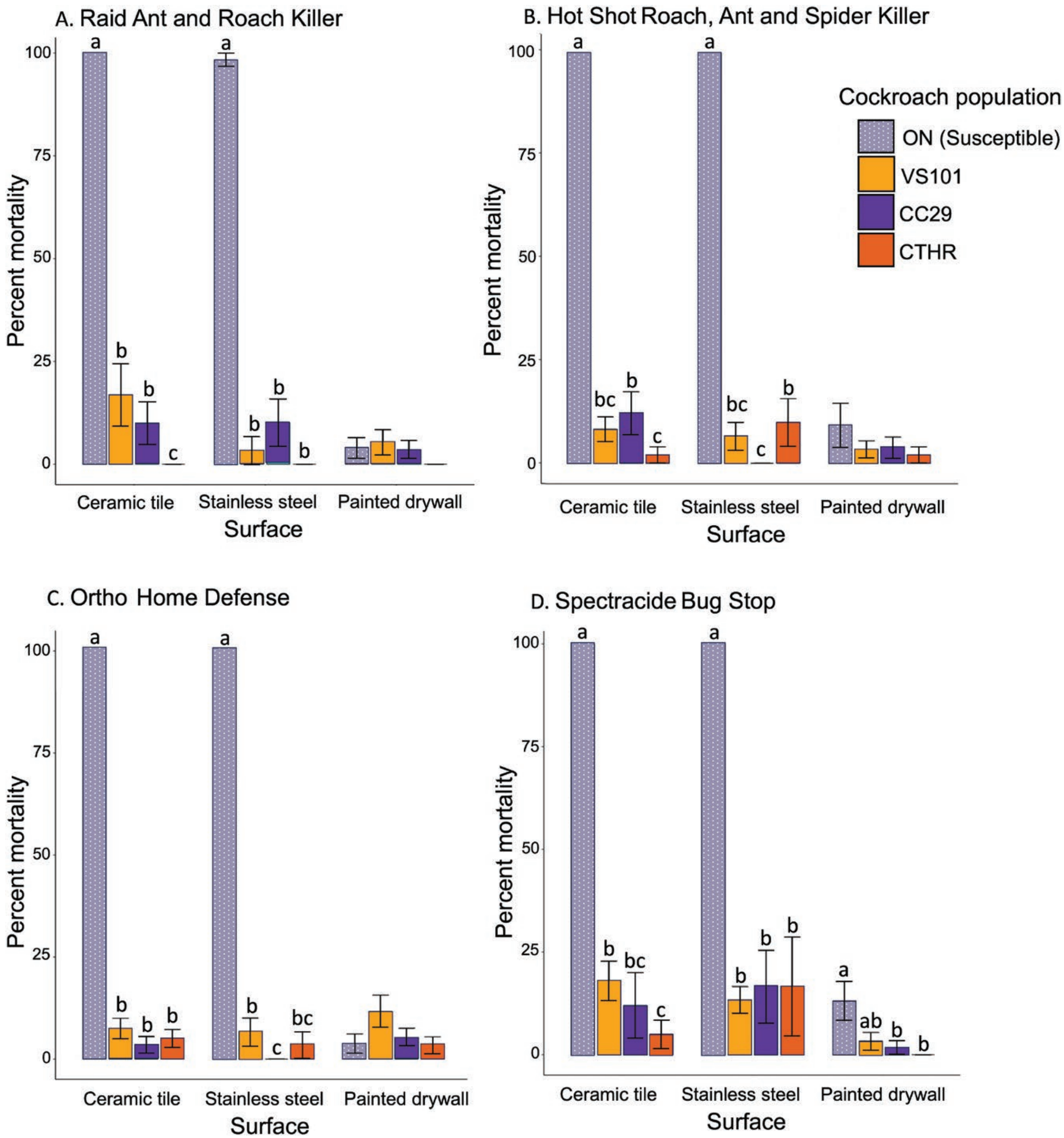

Figure 1. Percent mortality at 24 hr following limited exposure (30 min) to consumer-grade cockroach spray products (Hot Shot Roach, Ant and Spider Killer (A), Ortho Home Defense (B), Raid Ant and Roach Killer (C), and Spectracide Bug Stop (D)) compared across 4 German cockroach populations on 4 common household surfaces (Kruskal–Wallis test; $P < 0.05$). Error bars represent standard error. Different letters denote within-surface significant differences between populations for each surface (Dunn's test).

another, they did significantly differ from both Hot Shot Roach, Ant and Spider Killer and Spectracide Bug Stop (Table 3), with the latter causing mortality at a significantly faster rate. Regardless, across all replicates, at least 8–24 hr of continuous exposure was needed to achieve 100% mortality (Table 3).

Discussion

Our study represents an evaluation of contemporary pyrethroid-based liquid/aerosol products, marketed to consumers for cockroach control. Our findings suggest that, though most products have reasonable efficacy with direct exposure, mortality substantially decreases for all products when applied as residual contact insecticides. Additionally, of the surfaces commonly found in the home where these products may be applied, certain surfaces had significant negative impacts on the efficacy of these products on cockroach mortality.

Under 40 Code of Federal Regulations (CFR) Part 158 Subpart R, as of 3/18/24 the EPA requires that the performance standard for a product performance claim "must be greater than or equal to 90 percent" (EPA 2022). In direct application assays, 100% mortality was observed for all replicates with cockroaches from the susceptible population. This is expected, given the long duration this population has been kept in laboratory culture, without exposure to insecticides and thus, without opportunity for insecticide resistance development. Percent mortality after direct exposure was at or above 90% for many field populations as well, though product performance was reduced for certain field populations. In total, 4 out of 16 product–population combinations failed to achieve an average mortality at or above 90%: Hot Shot Roach, Ant and Spider Killer on CTHR and Ortho Home Defense on CC29, VS101, and CTHR (Table 2). This is concerning, as targeted application to the insect is a best-case scenario for efficacy. The majority of a cockroach infestation within a home will not be visible/accessible to be sprayed directly (Appel 2021). As such, efficacy with direct application has minimal translational relevance to predicting management success within a home.

Residual efficacy studies are therefore critical to determine how well a product will perform against cockroach populations outside of the lab. EPA guidelines for product performance (EPA 2019) require both porous and nonporous surfaces to be used for residual application studies. Our study evaluated the residual efficacy of products on multiple surfaces for both field-collected and laboratory-susceptible cockroaches. When cockroaches were exposed to treated surfaces for 30 min before being moved to a clean surface, mortality varied substantially by surface across products and between susceptible and field-collected cockroach populations. There was high mortality (~100%) of susceptible cockroaches for all tested products on both ceramic tile and stainless steel (Fig. 1), which was expected, given the lack of pyrethroid resistance development in susceptible populations and the expected higher efficacy of treatments on nonporous surfaces. However, mortality in the susceptible population was substantially lower for all products applied to painted drywall (Fig. 1), potentially due to the porous nature of this surface. It is surprising that mortality was so low, even for susceptible populations, on the porous surface, and suggests that these surfaces are not good candidates for product application inside the home.

In contrast, all product/surface combinations failed to achieve greater than 20% mortality for all field-collected populations. The limited efficacy of these products with limited exposure on 24-hr-aged surfaces in field-collected populations has substantial implications for residual efficacy on field populations, which, as highlighted above, likely have varying degrees of pyrethroid resistance owing to product overuse (Chai and Lee 2010, Fardisi et al. 2019). The EPA requirements for product labels state that, to include cockroaches on a label, the product must be tested on a single population of German cockroaches and a single population of American cockroaches. There is no requirement for the inclusion of recently collected field populations or for populations with demonstrated insecticide resistance. With limited exposure to product residues, the susceptible population had significantly higher mortality than all field populations on nonporous surfaces (Fig. 1). It is likely that the resistance status of a population correlates with the efficacy (or lack thereof) of pyrethroid-based residual insecticides. Pyrethroid resistance can develop through several mechanisms, including target site mutations such as *kdr* mutations (Dong et al. 1998, Scharf and Gondhalekar 2021) and increased detoxification enzyme activity, such as cytochrome P450 (Valles et al. 1994, Scharf et al. 1998). As such, testing of products on susceptible populations alone can give a false sense of efficacy—products may cause high mortality in laboratory trials, but would not necessarily have comparable efficacy on field populations within the home. Therefore, we argue that it is critical for products labeled for use on cockroaches to be tested using populations that have known pyrethroid resistance [e.g., >100-fold, DeVries et al. (2019b)] to increase the potential for product success in homes.

Differences in product formulations may have impacts on product efficacy. Two of the products evaluated in our study are formulated as ready-to-use (RTU) insecticides in water (Spectracide Bug Stop and Ortho Home Defense). The other 2 products we evaluated (Raid Ant and Roach Killer and Hot Shot Ant, Roach and Spider Killer) are formulated as RTU aerosols, which include the insecticide and a pressurized propellant that turns the liquid product into an aerosol mist once sprayed. It is likely that the solvent used to carry the insecticide (water vs. oil-based formulation) could lead to differential efficacy and differential interactions with different surfaces. For example, Raid Ant and Roach Killer is an oil-based aerosol, with petroleum distillates listed on the label. Petroleum oils are hypothesized to break down insect cuticle when sprayed on insects leading to mortality via desiccation (Appel 1990a, Stadler and Buteler 2009), which may contribute to additional insect mortality with direct sprays. Additionally, an oil-based formulation may be less likely to absorb into porous surfaces such as drywall or may chemically interact with plastic materials, such as vinyl, differently than they would with stainless steel or ceramic (Appel 1990a). These factors should be explored in future studies, along with other commonly used indoor surfaces, including painted and unpainted plywood.

Differences in active ingredients themselves may also impact efficacy. While all aerosol and spray products tested within our study and the majority of residual products marketed to consumers contain pyrethroids (Horton et al. 2011), structural differences between the pyrethroid active ingredients might lead to differences in efficacy. Some pyrethroids may perform better against field populations. In our study, Spectracide Bug Stop (0.025% gamma-cyhalothrin) and Hot Shot Roach, Ant and Spider Killer (0.075% imiprothrin,

Table 3. Predicted mean and median survival time based on Kaplan–Meier survivorship curves for field-collected German cockroaches (CTHR; collected in Lexington, KY in 2021) with continuous exposure to consumer-grade aerosol/liquid spray products applied to ceramic tile

Treatment	*n*	Predicted mean survival time (h)	Standard error (mean)	Predicted median survival time (h)	95% CI (median)	Range in time to 100% mortality (h)
Raid Ant and Roach Killer[a]	30	56.8	7.3	48	24.0–72.0	48–120
Hot Shot Roach, Ant and Spider Killer[b]	30	18.9	3.2	24	2.0–24.0	24–72
Ortho Home Defense[a]	30	64.3	6.7	72	48.0–72.0	72–120
Spectracide Bug Stop[b]	30	10.6	2.0	2	2.0–n/a	24–24
Control[c]	30	102.4	5.0	120	n/a	120–120

Different superscript lower-case letters indicate a significant difference in survivorship among populations (log-rank test; $P < 0.05$).

0.025% lambda-cyhalothrin) had the lowest mean survival times with exposure to product residues in continuous exposure assays (Table 3). In a 2008 survey (Starr et al. 2008) of household vacuum dust, imiprothrin and cyhalothrin had relatively low concentrations in collected dust (4 ng/mg dust and 7 ng/mg dust, respectively), which suggests lower relative use in 2008 compared to other pyrethroids such as permethrin and cypermethrin (85 ng/mg dust and 29 ng/mg dust, respectively). Similarly, Stout et al. (2009) found low incidence of imiprothrin (3%) and cyhalothrin (21%) in floor wipe samples, with much higher detection frequencies of permethrin (89%) and cypermethrin (46%). Pyrethroid actives that are used less frequently may be more effective than their higher-incidence-of-use counterparts. However, it is likely that, with continued use of these active ingredients, resistance will continue to develop.

While our study did not explore residual efficacy past 24 hr of aging on surfaces as did Blow (1978) and Chadwick (1985), it is unlikely, based on our results, that current DIY products would have improved efficacy with age. When we examined the labels on the DIY products tested in this study, the specified retreatment timeline ranges from "every 4 wk as necessary" for Raid Ant and Roach Killer, to 3 months for Hot Shot Roach, Ant and Spider Killer Roach & Spider Killer, to "up to 12 months for cockroaches on non-porous surfaces" for both Spectracide Bug Stop and Ortho Home Defense. Given the reduced mortality with exposure to freshly-dried products we found on all surfaces, it is unlikely that residual efficacy will improve when products have aged on surfaces for several weeks to several months, as described on these labels.

For crawling pests (e.g., cockroaches), the EPA states that the length of time the insect is in contact with a treated surface should be minimized (i.e., less than 4 hr; EPA 2019). Our exposure time of 30 min in our limited exposure residual efficacy trials is well within these guidelines. However, in an effort to give each product the maximum chance of working, we also conducted continuous exposure assays, where cockroaches were held on treated surfaces without food and water continuously. Surprisingly, it took at least 24 hr to achieve 100% mortality (depending on the product; Table 3). In reality, cockroaches would not likely spend that much time on treated surfaces. Recently, Gaire et al. (2024) found that while both susceptible and insecticide-resistant German cockroaches will freely walk across pyrethroid-treated surfaces, they will not arrest on these surfaces. As such, German cockroaches that encounter treated surfaces in a home will not stay on those surfaces for 3 d, let alone the ~10 hr of continuous exposure predicted to achieve mortality for the fastest working product in our study (predicted mean survival time of Spectracide Bug Stop; Table 3).

Lack of efficacy of these DIY products can not only perpetuate the consumer's feelings of hopelessness surrounding cockroach control (Wood et al. 1981, Shah et al. 2018), but increase desperation and lead people to misuse products, with disastrous results. On the national scale, there is widespread exposure to pyrethroids (Barr et al. 2010, Morgan 2012, Lehmler et al. 2020). In particular, perimeter application of spray products, second only to total-release foggers, introduce considerable insecticides into the indoor home environment (Keenan et al. 2010). Though considered to have low acute human toxicity, occupational exposure or accidental exposure through ingestion of pyrethroid insecticides may lead to dermal irritation, nausea and vomiting, and dizziness (He et al. 1989). More recent studies have explored the negative impacts of prenatal and childhood pyrethroid exposure on neurodevelopment (Andersen et al. 2022, Elser et al. 2022, Ntantu Nkinsa et al. 2023). Pyrethroid pesticide exposure was positively associated with hearing loss in US adolescents (Xu et al. 2020) and a case study of a toddler linked development of facial paresthesia to in-home applications of a pesticide product containing bifenthrin (0.05%) and zeta-cypermethrin (0.0125%) as active ingredients (Perkins et al. 2016).

The results of this study provide evidence for the lack of efficacy of pyrethroid-based DIY liquid/aerosol products. Thus, we recommend that other strategies for controlling cockroaches, such as the use of consumer bait products or professional pest control services, should be utilized by residents looking to control cockroaches over DIY spray products. While consumer granular and gel baits have shown good efficacy (Appel 1990b, 1992, El-Monairy et al. 2015, Lucero 2023), future work should conduct in-depth examinations of these and other pest control products marketed to consumers.

The high price of professional pest control is just one of many barriers to effective pest control in low-income housing. Lacking or ineffective pest management can drive residents to turn to readily available products that promise to control cockroaches and further lack of efficacy of these products can lead to the belief that cockroaches cannot be controlled in the home. Everyone deserves access to effective cockroach control and to live in a cockroach-free home and products available and marketed for cockroach control should be able to control cockroaches.

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Author contributions

Johnalyn Gordon (Data curation [equal], Formal analysis [lead], Investigation [supporting], Methodology [supporting], Validation [equal], Visualization [lead], Writing—original draft [lead], Writing—review & editing [equal]), Marla Eva (Investigation [lead], Writing—review & editing [equal]), Sudip Gaire (Conceptualization [equal], Methodology [equal], Writing—review & editing [equal]), Arthur Appel (Data curation [equal], Funding acquisition [equal], Investigation [eead], Project administration [equal], Resources [equal], Supervision [equal], Writing—review & editing [equal]), and Zachary DeVries (Conceptualization [equal], Funding acquisition [lead], Project administration [lead], Resources [lead], Supervision [lead], Validation [equal], Writing—review & editing [equal])

Supplementary data

Supplementary data are available at *Journal of Economic Entomology* online.

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Data availability

Study data are available in the supplementary materials.

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