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Research

Household and Structural Insects

Ineffectiveness of over-the-counter bait and aerosol insecticide products against field-collected German cockroaches (Blattodea: Ectobiidae)

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Over-the-counter (OTC) insecticide products are popular, easily available, and inexpensive do-it-yourself options for home residents. In this study, we investigated the performance of OTC insecticides consisting of bait and spray products against susceptible and field-collected strains of the German cockroach, *Blattella germanica* (L.) (Blattodea: Ectobiidae) using several test methods. In open arena bioassays, all OTC baits tested were ineffective on field-collected German cockroaches. The least effective OTC bait was unable to kill all test cockroaches of any strains at 14 d post-treatment. Direct spray experiments demonstrated that cockroaches treated with pyrethroid spray registered significantly shorter mean knockdown times when compared to that of the natural product. On the other hand, the natural product spray caused significantly shorter mean survival time in test insects than the pyrethroid spray (<1 h vs. >1 d). The residual efficacy of spray deposits was evaluated in the Ebeling choice box and revealed that all sprays have poor residual performance against field-collected German cockroach strains. Insecticide resistance and potential avoidance behavior may have contributed to the low performance index (PI) values of pyrethroid-based sprays, as cockroaches may have survived initial contact and subsequently avoided treated surfaces. Conversely, natural product spray deposits exhibited negative PI values for most of the study period due to spatial repellency. In general, the performance of OTC insecticide products was lower on field-collected German cockroach strains than on the susceptible strain. These products are likely ineffective at controlling the German cockroach infestations in homes.

Keywords: insecticidal baits, Ebeling choice box, aerosols, do-it-yourself pest control

Introduction

The German cockroach, *Blattella germanica* (L.), is an important indoor urban insect pest of public health importance, commonly found in residential and food preparation facilities (Lee and Wang 2021). Two significant health risks are associated with a German cockroach infestations in residential settings: (i) production of metabolites that can trigger allergies and asthma, and (ii) transmission of pathogenic microbes (also as vectors of antibiotic resistance genes) (Schal and DeVries 2021). A survey (the National Survey of Lead and Allergens in Housing) carried out by the US National Institute of Environmental Health Sciences (NIEHS) and the US Department of Housing and Urban Development (HUD) found detectable levels of the cockroach allergen *Bla g* 1 (originated from German cockroach) in >60% of homes, with higher concentrations in high-rise apartments, urban settings, and low-income houses (Cohn et al. 2006). Studies have also shown cockroach allergens are a significant cause of asthma morbidity, especially in inner-city homes (Rosenstreich et al. 1997, Gruchalla et al. 2005, Schal and DeVries 2021). As for the transmission of pathogenic microbes, no studies have definitively demonstrated an epidemiological link between cockroaches and infectious disease. However, cockroaches can move freely between waste and food, and pathogenic bacteria have been isolated from their bodies (Donkor 2019). Hence, their persistence in homes poses significant health risks to humans.

The control of the German cockroach has relied heavily on insecticides (Lee and Rust 2021). This has led to the development of insecticide resistance in the German cockroach (Scharf and Gondhalekar 2021, Lee et al. 2022a, 2022b). Reports indicate that German cockroaches are resistant to 45 active ingredients (AIs) across 132 sites globally (Scharf and Gondhalekar 2021, Mota-Sanchez and Wise 2024). It is a major challenge to the pest management industry worldwide.

Cockroach infestations disproportionately impact underserved communities due to ineffective pest control measures

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(Wang et al. 2019). The shortcomings of professional pest control services may, in part, be due to pest control contracts often being awarded to the lowest bidder. Therefore, the technicians would have to move and service each unit quickly and rely on residual sprays to further reduce costs (Miller and Meek 2004, Miller and Smith 2020). Dissatisfaction with the ineffective pest control services often leads to residents attempting to do the treatment by themselves using over-the-counter (OTC) insecticide products (Davies and Petranovic 1986, Wang et al. 2008). This carries a high risk of misapplication, with surveys showing that 65% of residents would apply insecticides on a routine basis regardless of the presence of pests (Dingha et al. 2013). This exacerbates the infestation further, potentially selecting for higher levels of insecticide resistance (Miller et al. 2021, Scharf and Gondhalekar 2021). There have been limited reports on the effectiveness of OTC insecticide products against German cockroaches (DeVries et al. 2019a, 2019b, Appel et al. 2022, Gordon et al. 2024, 2025).

In this study, we evaluated the effectiveness of commercial OTC sprays and baits against field-collected strains of the German cockroach. We used the dual-chamber method to assess the baits, while for the sprays, we used 2 approaches—the direct spray and Ebeling choice box methods. We discussed how insecticide resistance influences the performance of these products.

Materials and Methods

Insects

Five field strains of German cockroaches collected from various parts of California from 2018 to 2020, as well as the UCR susceptible strain, were used in this study. The resistance history and other information are provided in Table 1. The UCR strain was established in the 1980s from the susceptible Orlando Normal strain maintained by the ARS-USDA Laboratory in Gainesville, Florida. Since then, it has been reared in isolation at the University of California, Riverside, without any further population mixing or exposure to insecticides (Atkinson et al. 1991, Lee et al. 2022a, 2024). All insects were reared in either a 3.8-L glass jar or a 121-L polyethylene trash can bin fitted with a modified electrical barrier to prevent escape (Wagner et al. 1964). They were provided with dog food (Purina Dog Chow, Nestlé Purina Petcare, St Louis, Missouri, USA) and a water source ad libitum, and were reared in the laboratory under ambient conditions of 24 ± 2 °C, 30% to 50% RH, 12:12 h L: D photoperiod with corrugated cardboard used as harborages (Lee et al. 2022a).

Insecticides

All OTC products evaluated in this study were purchased from hardware stores or online sources. Information on them is provided in Table 2. AIs included fipronil, indoxacarb, boric acid, different pyrethroids, as well as various essential oils totaling 12 products. Three bait formulations were tested: Combat gel bait, Hot Shot bait station, and PiC gel bait. For the direct spray test, Zevo (a) and Black Flag were used, while the residual spray test included Black Flag, Ortho, Raid, Hot Shot spray, Safer, STEM, and Zevo (b). The 2 Zevo formulations, labeled (a) and (b), are marketed under similar product names but differ in their AIs and availability. These differences may be due to periodic updates made by the manufacturer. OFF! was included as a known spatial repellent (containing DEET) to serve as a positive control to validate the Ebeling choice-box assay's ability to detect repellency.

Bait Evaluation Using the Dual Chamber Method

The evaluation used the modified dual-chamber system based on Organization for Economic Co-operation and Development Standard (OECD 2013). Test arena consisted of a "harborage chamber" (28.7× 15.5 ×10.9 cm) and a "feeding chamber" of identical dimensions, interconnected by a Tygon tube (0.64 cm inner diameter ×10 cm long). A folded piece of corrugated cardboard was placed inside the harborage chamber to serve as the harborage. The feeding chamber was provisioned with bait, 3 pieces of dog food (Purina Dog Chow, Nestlé Purina Petcare, St Louis, Missouri, USA), and a water source to last the whole duration of the experiment (14 d). Ten adult male cockroaches were allowed to acclimate for 24 h before 1 g of bait (either Combat gel bait or PiC gel bait) placed in a weigh boat was introduced. The Hot Shot bait station was placed directly onto the feeding chamber. Control replicates were only provisioned with dog food, and the space designated for bait was left empty. The walls of the harborage and feeding chamber were lined with a thin layer of petroleum jelly + baby oil (3:2) mixture to prevent escape, while a sheet of paper was taped to the floor of the arena to increase traction for the cockroaches. Each bait evaluation was replicated 5 times for each of the 6 strains: 5 field-collected strains and 1 susceptible laboratory strain. Mortality was recorded every 4 h for the first 24 h, every 12 h for the first 7 d, and then daily until 14 d. Cockroaches were

Table 1. Information on German cockroach strains used in this study

Name	Collection location	Collection date	Resistance history[a]	Date tested for the current study
CDR	Vista, CA	2019	Clothianidin, deltamethrin, fipronil	2023 to 2024
RG386	Los Angeles, CA	2019	Clothianidin, deltamethrin, fipronil, indoxacarb	2023
Ryan	San Jose, CA	2020	Clothianidin, deltamethrin, fipronil, indoxacarb	2023 to 2024
SY	San Diego, CA	2019	Clothianidin, deltamethrin, fipronil, indoxacarb	2023 to 2024
WM	Los Angeles, CA	2018	Clothianidin, deltamethrin, fipronil	2023
UCR	Originally established from Orlando Normal strain maintained by ARS-USDA Laboratory in Gainesville, FL.[b]	1980s[c]	Susceptible laboratory strain; no history of insecticide exposure.	2023 to 2024

[a]From Lee et al. (2022a) diagnostic dose 3× LD_{95} treatment with <50% mortality after 72 h, based on topical bioassays using the UCR susceptible strain.
[b]Information from Atkinson et al. (1991).
[c]Exact year not recorded; strain was established in the 1980s.

Table 2. Information on OTC insecticide products used in this study

Product name	Designated name	Formulation	% active ingredient	Manufacturer/city of manufacture	EPA Reg. No.
Combat Max gel bait	Combat gel bait	Gel bait	0.01% fipronil	Henkel North American Consumer Goods, Stamford, CT	64240-45
Hot Shot MAXATTRAX	Hot Shot bait station	Bait station	0.1% indoxacarb	Spectrum Brands, Madison, WI	9688-193-8845
PiC gel bait	PiC gel bait	Gel bait	33.3% boric acid	PIC Corporation, Linden, NJ	3095-68
Black Flag Ant & Roach Killer	Black Flag	Aerosol	0.1% imiprothrin, 0.025% lambda-cyhalothrin	Spectrum Brands, Madison, WI	9688-246
Ortho Home Defense Insect Killer for Indoor & Perimeter	Ortho	Hand spray	0.05% bifenthrin, 0.0125% zeta-cypermethrin	The Scotts Miracle-Gro Company, Marysville, OH	239-2717
Raid Ant & Roach Killer 26	Raid	Aerosol	0.06% imiprothrin, 0.1% cypermethrin	S.C. Johnson & Son, Racine, WI	4822-596
Hot Shot Kitchen Bug Killer2	Hot Shot aerosol	Aerosol	0.02% pyrethrins, 1% piperonyl butoxide	Spectrum Brands, Madison, WI	9688-129-8845
Safer Home Ant, Roach, & Spider Killer	Safer	Aerosol	0.05% clove oil, 0.05% cottonseed oil	Woodstream Corporation, Lancaster, PA	-
STEM Kills Ants Roaches Flies	STEM	Hand spray	6.2% geraniol, 0.5% lemongrass oil	S.C. Johnson & Son, Racine, WI	-
Zevo Crawling Insect Killer—Ants, Roaches, Spider	Zevo (a)	Aerosol	1.3% geraniol, 0.2% cinnamon oil	The Procter & Gamble Company, Cincinnati, OH	-
Zevo Crawling Insect Killer—Ants, Roaches, Spider	Zevo (b)	Aerosol	5.96% sodium lauryl sulfate, 2.48% rosemary oil, 2.48% cornmint oil	The Procter & Gamble Company, Cincinnati, OH	-
OFF! Sportsmen Insect Repellent 1	OFF!	Hand spray	98.25% DEET	S.C. Johnson & Son, Racine, WI	4822-276

considered dead when they could not right themselves within 2 min after a gentle prod with forceps. Data were subjected to Kaplan–Meier survival analysis and log-rank test using SPSS version 29 (IBM Corporation, Armonk, New York, USA).

Direct Spray Test for Spray Formulations

The tests were conducted by confining 10 adult male German cockroaches to a piece of treated plywood with a glass cylinder (6.5 cm diameter × 7.5 cm height) lined with fluon to prevent escape. Each spray formulation was applied by spraying it from 50 cm away at 45-degree angle for 1 s. Instead of evaluating all spray products, we only selected 2 OTC sprays, Zevo (a) and Black Flag, for the direct spray tests to represent the 2 major categories of consumer spray formulations: natural product-based (Zevo [a]) and synthetic pyrethroid-based (Black Flag). The average dispense rate is 3.7 g/s for Zevo (a) and 4.0 g/s for Black Flag with AI delivery rates at 55.24 mg/s and 5.00 mg/s, respectively (Table 3). After the insecticide application, the insects were video-recorded using an iPhone 7 (Apple Inc., Cupertino, California, USA) under natural lighting. Videos were manually reviewed using playback controls in DaVinci Resolve 18 (Blackmagic Design Pty Ltd, Melbourne, Australia) to observe knockdown over a 5-min period. After 3 h, they were transferred into a clean polyethylene container (8.5 cm diameter×7.5 cm height) lined with fluon to prevent escape and provided with 1 piece of dog food (Purina Dog Chow, Nestlé Purina Petcare, St Louis, Missouri, USA) and a water source that were sufficient for duration of the experiment (3 d), and folded corrugated cardboard to serve as harborage. Controls were sprayed with deionized water. Mortality was recorded daily for up to 3 d. Insects were considered knocked down when they could not coordinate movement or right themselves. Insects were considered dead when they were unable to right themselves within 2 min and did not respond to gentle prodding with forceps. Each spray formulation was tested 5 times on the UCR strain and repeated for the Ryan and CDR strains. Data were subjected to Wilcoxon signed-rank test, Kaplan–Meier survival analysis, and log-rank test using SPSS version 29 (IBM Corporation, Armonk, New York, USA).

Table 3. Approximated amount of AIs dispensed from OTC sprays per 1 s spray

Sprays	1 s spray avg. weight (g)	AI ± SEM (mg)	Maximum amount AI on panel[a] (mg/cm²)
Black Flag	4.0	5.00 ± 0.2	0.01
Ortho	4.5	2.79 ± 0.0	0.01
Raid	3.5	5.63 ± 0.4	0.01
Hot Shot spray	2.3	23.34 ± 0.6	0.05
Safer	4.2	4.22 ± 0.1	0.01
STEM	2.5	165.10 ± 0.8	0.36
Zevo (a)	3.7	55.24 ± 1.1	-
Zevo (b)	7.4	807.51 ± 20.7	1.74
OFF!	2.3	2307.00 ± 28.5	4.98

[a]Maximum amount of AI on vinyl floor panel (15.2×30.5 cm).

Evaluation of Residual Spray Deposits Using Ebeling Choice Box

The Ebeling choice box has been used to determine the toxicity, repellency, and potential performance of various insecticides in dusts, sprays, and baits (Ebeling et al. 1966, Appel et al.

2022). The choice box is a square wooden box with a Masonite floor and a wooden vertical partition that separates the box into 2 equal sides (30.5×15.2×9.5 cm). The wooden vertical partition has a hole near the middle top portion, allowing cockroaches to move freely between the 2 sides of the box.

For this evaluation, 8 spray formulations were tested: (i) Black Flag, (ii) Ortho, (iii) Raid, (iv) Hot Shot spray, (v) Safer, (vi) STEM, (vii) Zevo (b), and (viii) OFF!. This is because residual spray is a common cockroach management approach used by both residents and pest management professionals. In addition, the residual efficacy of natural product-based sprays is not well understood, prompting a broader investigation across different formulations. Vinyl flooring panels (Tarkett SA, Paris, France) were cut to size (15.2 × 30.5 cm), sprayed uniformly at a 45-degree angle for 1 s, and allowed to dry for 24 h. The maximum amount of AI uniformly distributed on the vinyl flooring panels was calculated based on the average weight of OTC sprays dispensed in 1 s into a sealable bag (to prevent dispersion and evaporation) (Table 3). After the 24 h drying period, the panel was then placed into the dark side of the choice box. Three pieces of dog food (Purina Dog Chow, Nestlé Purina Petcare, St Louis, Missouri, USA), a water source sufficient for duration of the experiment (14 d) were placed in the light side of the box. Both sides of the box were covered with transparent sheets of Lucite. The dark side was covered with another sheet of Masonite. Twenty adult male German cockroaches were introduced into the light side, and a piece of cork was placed in the partition hole to let the cockroaches acclimate for 4 to 5 h. After that, the cork was removed to allow the cockroaches to freely access both the light and dark compartments of the box. Vinyl flooring panels were sprayed with deionized water for the untreated controls.

The choice boxes were exposed to a photoperiod of 12:12 h (L: D). The test was replicated 3 times for each combination of spray formulation and strain. The location of the cockroaches and status (alive or dead) were recorded for 14 d to calculate the performance index (PI). The PI estimates potential field performance by combining mortality and repellency effects:

$$PI = \left[1 - \left(\frac{Total\ number\ alive + Number\ alive\ in\ light\ side}{Total\ number\ dead + Initial\ total\ number}\right)\right] \times 100.$$

The values for PI range from −100 (complete repellency) to 100 (complete mortality), with 0 equating to no repellency nor mortality (Rust and Reierson 1978). The PI at 7 and 14 d were subjected to Kruskal–Wallis test using JMP Pro 17 (SAS Institute, Cary, North Carolina, USA).

Results

Bait Evaluation Using the Dual Chamber Method

All 3 OTC baits, Combat gel bait, Hot Shot bait station, and PiC gel bait, showed reduced performance against most field-collected strains when compared to the UCR susceptible strain in the log-rank tests except for WM and RG386 (Fig. 1A–C). The mortality of field-collected strains of German cockroaches at 14 d varied by strain, ranging from 42.5% to 100% for Combat gel bait, 57.5% to 97.5% for Hot Shot bait station, and 32.5% to 52.5% for PiC gel bait (Table 4). The WM strain was the least resistant field strain tested with the shortest mean survival time and consistently overlapped 95% CI with the UCR susceptible strain (Table 4, Fig. 1A–C). Both the performance of Combat gel bait and Hot Shot bait station varied from >95% mortality at 14 d in WM and RG386 to <60% in SY and CDR (Table 4, Fig. 1A and B). The mortality of all cockroach strains provided by PiC gel bait was poor. At 14 d, the UCR susceptible strain displayed 77.5% mortality, while each of the field-collected strains tested showed <60% mortality. No significant differences were found between most strains, which may be due to limited consumption or the slow-acting nature of the AI (boric acid) (Table 4, Fig. 1C).

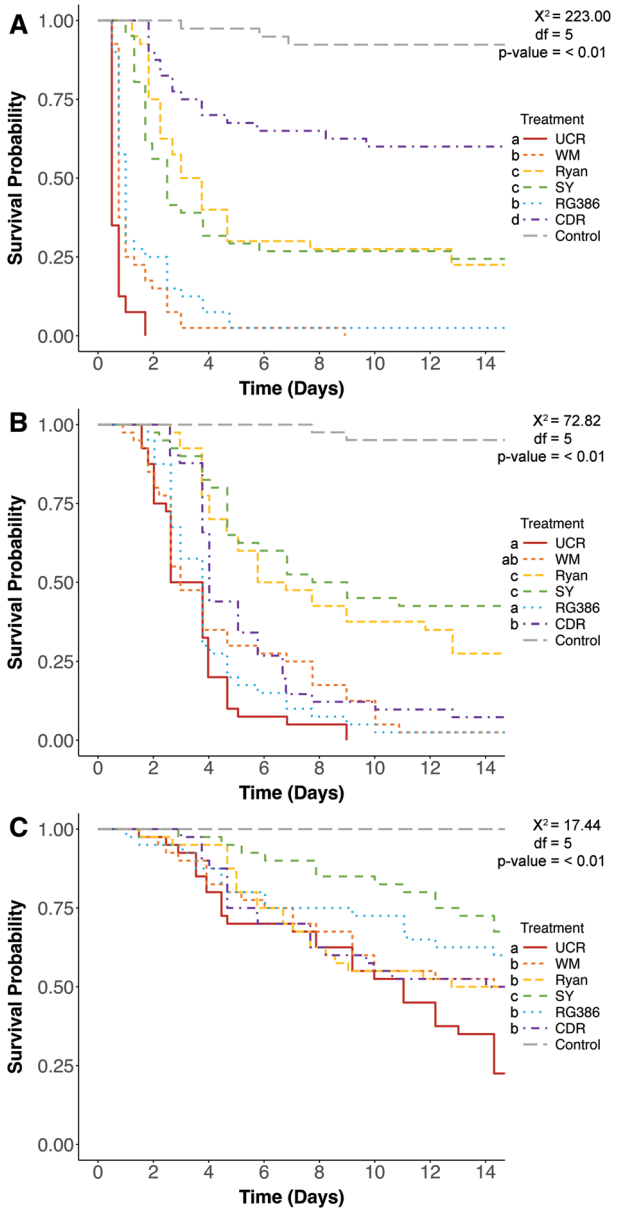

Fig. 1. Survivorship of adult male German cockroaches treated with OTC baits: A) Combat gel bait (0.01% fipronil), B) Hot Shot bait station (0.1% indoxacarb), and C) PiC gel bait (33.3% boric acid), tested against the following German cockroach strains: UCR (susceptible), WM, Ryan, SY, RG386, and CDR. Different letters in the figure legend indicate significant differences between strains ($P < 0.05$).

Table 4. Mean survival time and total mortality of cockroach strains in OTC bait evaluations

Bait (% active)	Strain	Mean survival time (d)	95% CI	Standard error	% Mortality at 14 d
Combat gel bait (0.01% fipronil)	UCR	0.67	0.569 to 0.775	0.052	100
	WM	1.30	0.865 to 1.741	0.224	100
	Ryan	6.11	4.441 to 7.774	0.85	77.5
	SY	5.62	3.884 to 7.345	0.883	75.6
	RG386	1.77	1.026 to 2.516	0.38	97.5
	CDR	10.45	8.665 to 12.233	0.91	42.5
Hot Shot bait station (0.1% indoxacarb)	UCR	3.49	2.952 to 4.022	0.273	100
	WM	4.65	3.633 to 5.67	0.52	97.5
	Ryan	8.53	7.022 to 10.031	0.767	75
	SY	9.41	7.825 to 10.986	0.807	57.5
	RG386	4.21	3.425 to 4.995	0.4	97.5
	CDR	5.61	4.606 to 6.61	0.511	97.5
PiC gel bait (33.3% boric acid)	UCR	9.82	8.385 to 11.263	0.734	77.5
	WM	10.82	9.313 to 12.318	0.767	50
	Ryan	10.77	9.335 to 12.201	0.731	52.5
	SY	13.16	12.108 to 14.213	0.537	32.5
	RG386	11.68	10.196 to 13.169	0.758	40
	CDR	10.72	9.251 to 12.183	0.748	50

Direct Spray Test for Aerosol Formulations

Black Flag exhibited significantly faster mean knockdown times than Zevo (a) across all tested insect strains, except when tested against the Ryan strain. This difference was statistically significant for both the UCR and CDR strains ($P < 0.001$), but not for the Ryan strain ($P = 0.289$; Wilcoxon signed-rank test). All German cockroach tested were knocked down regardless of strains when directly sprayed with Zevo (a) and Black Flag (Fig. 2A and B, Table 5). The mean knockdown time for Black Flag was 5.5 ± 0.017, 8.6 ± 0.023, and 27.2 ± 0.082 s for the UCR, CDR, and Ryan strains, respectively, while for Zevo (a), it was 18.0 ± 0.034, 26.5 ± 0.061, and 28.2 ± 0.068 s.

The fast knockdown time caused by Black Flag relative to Zevo (a) did not reflect the mean survival time after treatment. For Zevo (a), knockdown and mortality were closely related; once the insects lost the ability to right themselves, they subsequently stopped responding to external stimuli, including gentle prodding with forceps. In contrast, with Black Flag, insects often exhibited rapid knockdown but either continued responding to prodding or later recovered normal activity. The mean survival times of Zevo (a) for both susceptible and field-collected strains were <1 h, whereas the mean survival times of Black Flag for the susceptible strain was 18.5 h and for field-collected strains were >24 h (Table 6, Fig. 3A and B). Log rank tests confirmed the significantly reduced efficacy of Black Flag, which failed to achieve complete mortality in the Ryan strain by 72 h post-treatment (Table 6).

Evaluation of Residual Spray Deposits Using Ebeling Choice Box

No statistically significant differences were found between any treatments and controls across strains (Supplementary Table S1). However, trends in the data indicated that the PI values of Raid and Ortho were the highest among all spray residuals tested for both susceptible and field strains (Fig. 4A–D). The residual deposits from these sprays resulted in PI values >80 at 14 d for the UCR strain (Fig. 4A), but lower PI values were observed for the field-collected Ryan, CDR, and SY strains, with PI values <52 at 14 d (Fig. 4B–D). The Black Flag spray had the lowest PI among the pyrethroid-based sprays, with a PI value of 25 at 14 d in the UCR strain, and <14 in all field strains (Fig. 4A–D). The natural product sprays Hot Shot, Safer, STEM, and Zevo (b) had negative PI values, which may reflect repellency effects (Fig. 4A–D). STEM had the most negative PI for the Ryan strain (PI = −29.69 at 14 d), Zevo (b) for the SY strain (PI = −24.59 at 14 d), and Hot Shot for the CDR strain (PI = −42.62 at 14 d). The OFF! spray, included as a positive control, also showed negative PI values throughout the study period across all strains, suggesting that the choice box assay could be used to detect spatial repellency. Although these differences were not statistically significant, they provide descriptive context for potential variation in product performance.

Discussion

OTC baits are an easily accessible option for DIY cockroach management. Various benefits of using baits to control cockroach infestation include reduced environmental contamination, precision in targeting cockroach infestation, and relative ease of application for consumers (Appel 1990, 1992, Reierson 1995). Baits are often packaged and sold as gel tubes or containerized stations where they can be applied and replenished. In particular, bait stations are highly consumer friendly as they are also child/pet tamper-proof.

We evaluated 3 consumer cockroach baits: Combat gel bait, Hot Shot bait station, and PiC gel bait. The Combat gel bait and Hot Shot bait station have 0.01% fipronil and 0.1% indoxacarb as their AIs, respectively. Both fipronil and indoxacarb target the insect's nervous system, with fipronil acting on the gamma-aminobutyric acid (GABA) receptors and indoxacarb on the voltage-gated sodium channels (Yu 2014). Fipronil is both a contact and oral poison (Buczkowski and Schal 2001). Previous studies have shown fipronil bait to be attractive and highly palatable, demonstrating a lack of repellency (Durier and Rivault 1999, 2000). Both factors likely contribute to the low mean survival time observed in our bait evaluation. In the

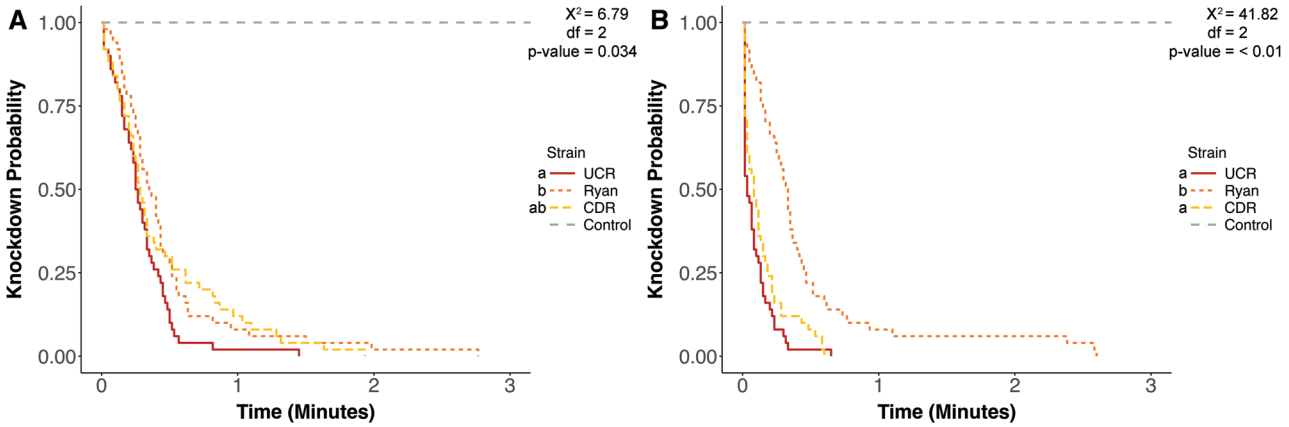

Fig. 2. Knockdown of adult male German cockroaches directly sprayed with OTC sprays: A) Zevo (a) (1.3% geraniol, 0.2% cinnamon oil) and B) Black Flag (0.1% imiprothrin, 0.025% lambda-cyhalothrin), tested against the following German cockroach strains: UCR (susceptible), Ryan, and CDR. Different letters in the figure legend indicate significant differences between strains ($P < 0.05$).

Table 5. Mean knockdown time of cockroach strains in OTC direct spray evaluations

Aerosol (% active)	Strain	Mean knockdown time (mins)	95% CI	Std. error
Zevo (a)	UCR	0.30	0.233 to 0.365	0.034
(1.3% geraniol,	Ryan	0.47	0.339 to 0.606	0.068
0.2% Cinnamon oil)	CDR	0.44	0.321 to 0.561	0.061
Black Flag	UCR	0.09	0.059 to 0.125	0.017
(0.1% imiprothrin,	Ryan	0.45	0.294 to 0.613	0.082
0.025% lambda-cyhalothrin)	CDR	0.14	0.097 to 0.189	0.023

Ebeling choice box, indoxacarb bait was nonrepellent and toxic (Appel 2003). Conversely, bait formulations containing boric acid were less effective and appeared to be less palatable, as suggested by the minimal feeding activity observed during our trials (Strong et al. 1993, Durier and Rivault 1999, Nalyanya et al. 2001). Additionally, laboratory and field tests have shown that boric acid-containing baits act more slowly and have inconsistent performance (Appel 1990, Gore and Schal 2004).

Ultimately, all tested bait formulations did not achieve complete mortality against field-collected strains by 14 d, except for Combat gel bait against the WM strain. This result is consistent with Appel et al. (2022), who found that Combat gel bait was active against German cockroaches; however, its performance was reduced in field-collected strains. Despite performing better than other OTC bait formulations in our study, it still failed to achieve total mortality in most strains tested. In addition, the specificity of the bait matrices remains proprietary, making it difficult to determine how other ingredients may contribute to bait performance. OTC formulations also typically contain lower concentrations of AIs compared to their professional counterparts. However, bait performance is not determined by AI concentration alone. Factors such as insecticide resistance of the field-collected strains, bait palatability, and matrix composition also likely contributed to the poor performance we observed and may explain the reduced effectiveness of these baits in the field.

Our findings are also in line with Gordon et al. (2025), who reported that while consumer-grade baits such as Combat gel and Hot Shot bait stations showed high efficacy in laboratory trials, their performance in field settings was often inconsistent or delayed. The discrepancy between laboratory and field results is concerning, especially given that even under controlled conditions these baits were unable to achieve complete mortality. This suggests that they are unlikely to be effective under field conditions and highlights the need for field validation of the performance of these OTC products.

Interestingly, our results showed that Combat gel bait, an OTC product containing 0.01% fipronil, achieved higher mortality in the same field-collected strains than a professional bait containing 0.05% fipronil tested by Lee et al. (2022a). The Ryan strain showed approximately 75% mortality in our study at 14 d, but only 50% mortality at 14 d in the earlier evaluation. This outcome may reflect the differences in bait matrix, which can influence palatability, or a potential decline in resistance levels over time in Ryan strain in the absence of continuous selection pressure. These findings reinforce that bait performance should not be determined solely based on AI concentration alone.

Most residents are familiar with insecticidal spray products. These formulations are relatively inexpensive, easy to use, and widely available. Surveys suggest that sprays are the most commonly practiced pest management strategies used by residents (Dingha et al. 2013). Insecticide spray products typically contain pyrethroids as the AI. However, over the past decade, essential oil-based sprays have gained increasing prominence due to consumer preference over products that are perceived to be safe to humans and pets (Koul et al. 2008, Oladipupo et al. 2022). Another driving force behind the growing number of natural product sprays on the market is that these formulations are exempted from the US Environmental Protection Agency (EPA) registration requirements under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) provision

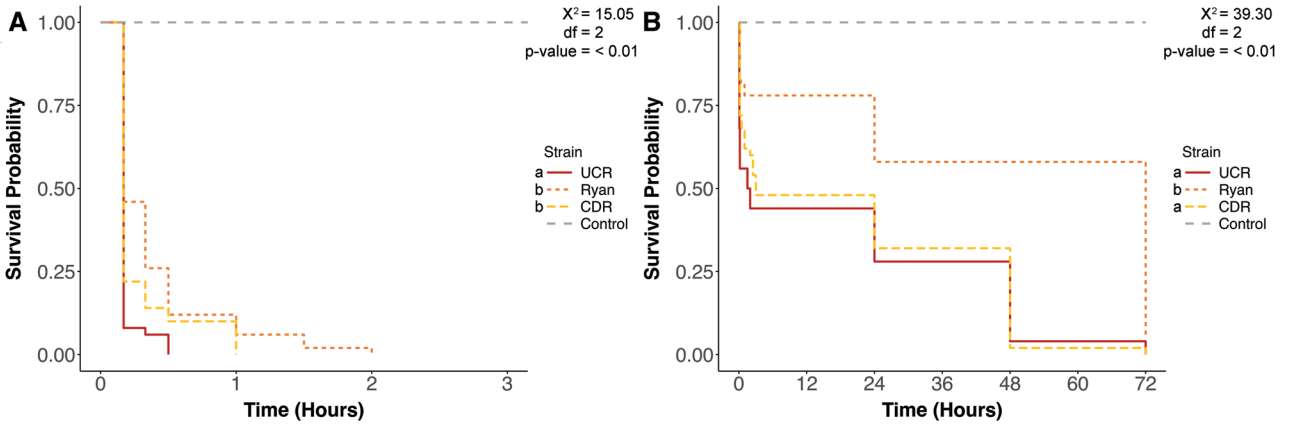

Fig. 3. Survivorship of adult male German cockroaches directly sprayed with OTC sprays: A) Zevo (a) (1.3% geraniol, 0.2% cinnamon oil) and B) Black Flag (0.1% imiprothrin, 0.025% lambda-cyhalothrin), tested against the following German cockroach strains: UCR (susceptible), Ryan, and CDR. Different letters in the figure legend indicate significant differences between strains ($P < 0.05$).

Table 6. Mean survival time and total mortality of cockroach strains in OTC direct spray evaluations

Aerosol (% active)	Strain	Mean survival time (h)	95% CI	Std. error	% Mortality at 72 h
Zevo (a)	UCR	0.19	0.17 to 0.216	0.012	100
(1.3% geraniol,	Ryan	0.39	0.279 to 0.497	0.056	100
0.2% Cinnamon oil)	CDR	0.28	0.208 to 0.35	0.036	100
Black Flag	UCR	18.50	12.176 to 24.829	3.228	100
(0.1% imiprothrin,	Ryan	46.63	38.011 to 55.257	4.4	94
0.025% lambda-cyhalothrin)	CDR	20.18	14.036 to 26.318	3.133	100

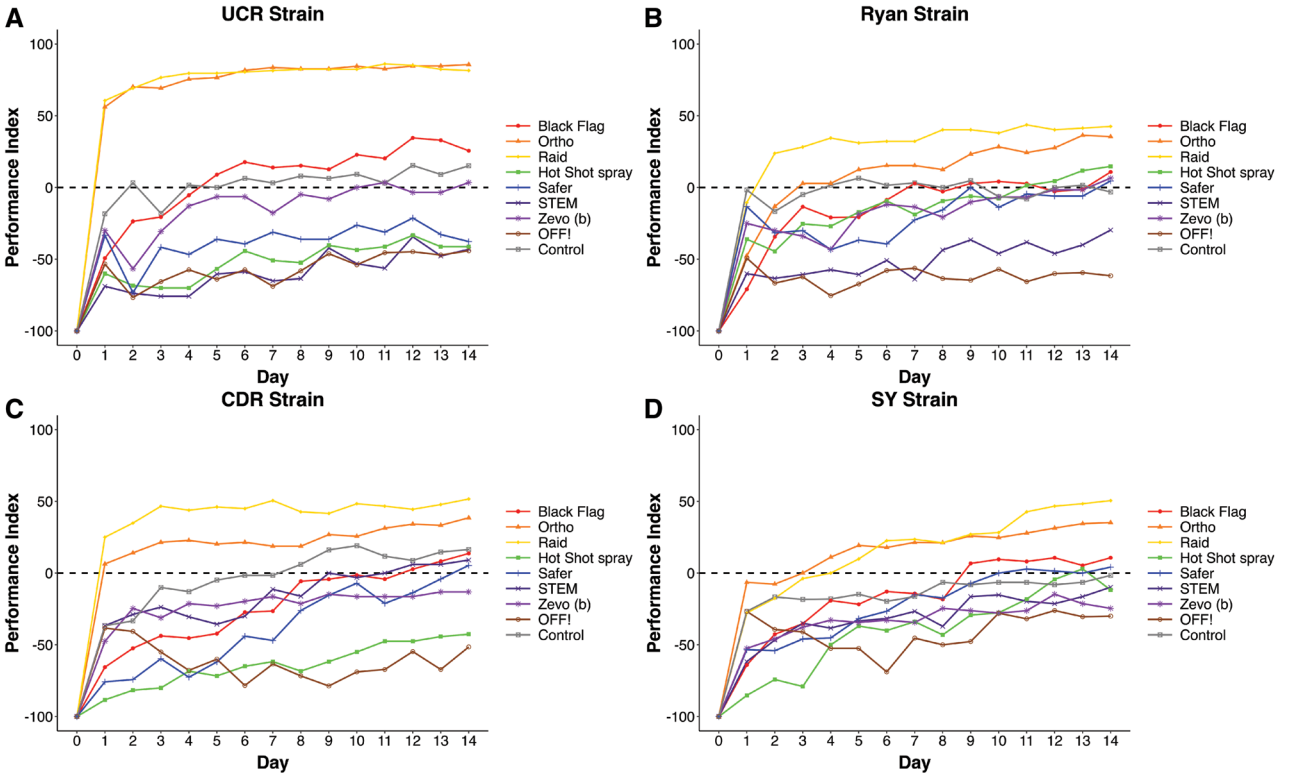

Fig. 4. Performance index of OTC spray residual deposits: Black Flag (0.1% imiprothrin, 0.025% lambda-cyhalothrin), Ortho (0.05% bifenthrin, 0.0125% zeta-cypermethrin), Raid (0.06% imiprothrin, 0.1% cypermethrin), Hot Shot spray (0.02% pyrethrins, 1% piperonyl butoxide), Safer (0.05% clove oil, 0.05% cottonseed oil), STEM (6.2% geraniol, 0.5% lemongrass oil), Zevo (b) (5.96% sodium lauryl sulfate, 2.48% rosemary oil, 2.48% cornmint oil), and OFF! (98.25% DEET), tested against German cockroach strains: A) UCR (susceptible), B) Ryan, C) CDR, and D) SY, using Ebeling choice boxes.

(EPA 2022). This provision states that certain active and inert ingredients (25B) can be exempted from EPA registration, allowing manufacturers to develop and sell natural product insecticides while bypassing any regulations and standards. We tested 8 OTC sprays (3 pyrethroid sprays and 5 natural product sprays) and 1 repellent spray. When diluted according to label instructions, professional pyrethroid spray formulations typically contained AI concentrations similar to those in OTC sprays (Sims et al. 2010, Rust et al. 2022, Table 3). Natural product sprays, however, generally contained higher concentrations of essential oil AIs (up to 2% in 1 product we evaluated), compared to the much lower pyrethroid concentrations (≤0.1% in the synthetic OTC sprays we evaluated).

In our direct spray tests, faster knockdown times were achieved with pyrethroid sprays than with natural product sprays, which is expected as pyrethroids are known for their rapid knockdown action (Matsuo 2019). However, the opposite pattern was observed for mean survival times. Cockroaches treated with pyrethroid sprays survived longer than those treated with natural product sprays, with some recovering after direct exposure. The delayed mortality is likely due to insecticide resistance, which reduces German cockroach susceptibility to pyrethroids through mechanisms such as metabolic detoxification and target-site insensitivity (Scharf and Gondhalekar 2021). Similar findings of incomplete mortality following pyrethroid exposure have been reported by Gordon et al. (2024), and factors such as resistance history and/or spray droplet size may also contribute to treatment failure (Wickham et al. 1974). In contrast, complete mortality was observed in natural product spray exposures in under 1 h. While their mode of action is unclear, these compounds may override resistance mechanisms. The natural product spray used in the direct exposure test, Zevo (a), contains geraniol and cinnamon oil as AIs. Constituents of cinnamon oil, such as eugenol, are likely responsible for the toxicity observed in this formulation (Phillips et al. 2010, Kim et al. 2015). Nevertheless, direct spray application is not an optimal cockroach management strategy, as it only targets visible individuals while most of the infestation remains concealed and inaccessible (Lee and Rust 2021).

The conventional pyrethroid sprays used in our tests were all advertised as having residual effects, whereas while the natural product sprays were not, they may exhibit residual repellency. Given their current prominence in the market, it is relevant to evaluate their residual efficacy. Natural product sprays have become desirable as a substitute for synthetic chemical sprays, in part because their volatility and rapid evaporation are believed to limit environmental persistence (Oladipupo et al. 2022). We used nonporous surface vinyl flooring tiles and the choice box to evaluate the residual and to predict potential field performance of these sprays (Rust and Reierson 1978, Rust et al. 1993).

The residual deposits of the conventional pyrethroid-based sprays were unable to kill all test insects at 14 d (Fig. 4A). The inability to achieve complete mortality may be partly due to insects behavioral avoidance of the treated surfaces over time (Ebeling et al. 1966, Gaire et al. 2024). The toxicity of pyrethroid spray residual deposits was reduced when tested against the field-collected strains. Decreased susceptibility toward pyrethroids in these strains was likely because of pyrethroid resistance (Lee et al. 2022a, 2022b). The natural product residual deposits are believed to lose toxicity due to volatility and evaporation, although this was not directly assessed in our study. Their repellent effect, however, appeared to persist longer, likely due to formulation characteristics (González et al. 2016). This is supported by our results for the OFF! spray, which consistently showed negative PI values across all strains. This suggests that the choice box assay is an effective method to detect spatial repellency.

Our results are consistent with Gordon et al. (2024), who evaluated the efficacy of consumer-grade pyrethroid sprays using direct, limited, and continuous exposure assays. Their study found that while most products were effective with direct application, residual performance was poor, especially under limited-contact scenarios. This is similar to our findings, where direct spray applications caused rapid knockdown, but residual deposits tested in the choice box offered limited control against cockroaches.

The lack of significant differences between the deposits may be attributed to a combination of avoidance behavior toward pyrethroid-based spray deposits, the steady decline of natural product repellency, and a relatively low sample size, which may have limited the power of our non-parametric comparisons. Nevertheless, the incomplete mortality caused by pyrethroid deposits may further select for insecticide resistance over time. Unless applied directly, natural product residues may offer limited benefit for cockroach control, and their repellency could potentially disperse infestations to other areas, ultimately undermining control efforts.

Insecticide resistance is one of the most significant challenges in German cockroach management. Our results highlight the ineffectiveness of OTC insecticide products against field-collected strains. The German cockroach has demonstrated the ability to develop resistance to nearly every AI currently on the market (Scharf and Gondhalekar 2021, Lee et al. 2022a). Resistance is often driven by repeated use of ineffective formulations and suboptimal application strategies. Inadequate treatments leave behind a portion of the population that can act as a reservoir for resistant alleles, leading to the proliferation of resistant German cockroaches over time. In the context of OTC products, limited efficacy combined with consumer misuse may accelerate the selection of resistant populations in the field.

In addition to physiological resistance, behavioral responses such as repellency can also impact insecticide performance. In the past studies using the Ebeling choice box, cockroaches have been observed avoiding toxic deposits, which reduce the effectiveness of insecticide formulations in cockroach management (Appel 2004, Rust et al. 2022). The PI calculated from the choice box shows the toxicity and their avoidance of insecticides (Rust and Reierson 1978). Repellency can occur in several forms, including spatial repellency (avoidance without contact), contact irritancy (insects leave after brief contact), and olfactory-mediated repellency (airborne compounds deter insects before physical contact) (Boné et al. 2020, Gaire et al. 2024). Pyrethroids can induce repellency through olfactory pathways, contact irritancy, or both. If insects are not deterred by olfactory cues and encounter the deposits, they may either receive a lethal dose or subsequently avoid further contact following sublethal exposure (Gaire et al. 2024). Unlike pyrethroids, essential oils are consistently associated with spatial repellency in cockroaches (Yoon et al. 2009, Phillips et al. 2010, Huang et al. 2020). The repellent effects may be helpful in preventing cockroach infestations if used proactively, even in multi-unit dwellings, by deterring cockroaches from entering a unit. However, they could be problematic when used reactively during an

active infestation. In response to repellent compounds, cockroaches may simply move from 1 unit to another, which does not eliminate the existing infestation problem and could potentially facilitate its spread to multiple locations (Miller et al. 2021).

Recent studies have evaluated consumer insecticide products, but comprehensive assessments remain limited considering their widespread availability and potential impact on German cockroach management overall (Appel 1990, DeVries et al. 2019a, Appel et al. 2022, Gordon et al. 2024, 2025). In our study, OTC baits and sprays are shown to have limited performance, and their efficacy is further reduced when tested against field-collected strain of German cockroaches. All bait products evaluated failed to eliminate field-collected cockroach strain, similar to previous studies (Appel et al. 2022, Lee et al. 2022a). Direct spray tests showed that both pyrethroid and natural sprays were effective in knocking down insects, but mortality was incomplete with pyrethroid sprays in some cases, consistent with previous findings (Gordon et al. 2024). Evaluations of residual spray deposits using Ebeling choice boxes showed reduced efficacy of conventional pyrethroid spray deposits against field-collected strains of the German cockroach. In contrast, natural product spray deposits were repellent and did not produce measurable toxicity, as indicated by negative PI values. Our findings suggest that the reduced performance of OTC insecticide sprays is due to insecticide resistance and behavioral repellency. In contrast, OTC bait performance was constrained by a combination of insecticide resistance, AI concentrations, and potentially unappealing bait matrices that reduced consumption. Potential control failures from using these products could further contribute to insecticide resistance in the field population.

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Author Contributions

Rattanan Chungsawat (Data curation [lead], Formal analysis [lead], Investigation [lead], Methodology [equal], Software [lead], Validation [lead], Visualization [lead], Writing—original draft [lead], Writing—review & editing [lead]), Dong-Hwan Choe (Resources [supporting], Supervision [supporting], Writing—review & editing [supporting]), Michael K. Rust (Conceptualization [supporting], Methodology [supporting], Project administration [supporting], Resources [supporting], Supervision [equal], Writing—review & editing [supporting]), and Chow-Yang Lee (Conceptualization [lead], Funding acquisition [lead], Methodology [equal], Project administration [lead], Resources [lead], Supervision [lead], Writing—original draft [supporting], Writing—review & editing [supporting])

Supplementary Material

Supplementary material is available at *Journal of Economic Entomology* online.

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Conflicts of Interest

The authors declare no conflict of interest.

References

Appel AG. 1990. Laboratory and field performance of consumer bait products for German cockroach (Dictyoptera: Blattellidae) control. *J. Econ. Entomol.* 83:153–159. https://doi.org/10.1093/jee/83.1.135a

Appel AG. 1992. Performance of gel and paste bait products for German cockroach (Dictyoptera: Blattellidae) control: laboratory and field studies. *J. Econ. Entomol.* 85:1176–1183. https://doi.org/10.1093/jee/85.4.1176

Appel AG. 2003. Laboratory and field performance of an indoxacarb bait against German cockroaches (Dictyoptera: Blattellidae). *J. Econ. Entomol.* 96:863–870. https://doi.org/10.1603/0022-0493-96.3.863

Appel AG. 2004. Contamination affects the performance of insecticidal baits against German cockroaches (Dictyoptera: Blattellidae). *J. Econ. Entomol.* 97:2035–2042. https://doi.org/10.1093/jee/97.6.2035

Appel AG, Dingha BN, Eva MJ, et al. 2022. Toxicity, repellency, and laboratory performance of consumer bait products for German cockroach (Blattodea: Ectobiidae) management. *Fla. Entomol.* 105:115–125. https://doi.org/10.1653/024.105.0203

Atkinson TH, Wadleigh RW, Koehler PG, et al. 1991. Pyrethroid resistance and synergism in a field strain of the German cockroach (Dictyoptera: Blattellidae). *J. Econ. Entomol.* 84:1247–1250. https://doi.org/10.1093/jee/84.4.1247

Boné E, González-Audino PA, Sfara V. 2020. Spatial repellency caused by volatile pyrethroids is olfactory-mediated in the German cockroach *Blattella germanica* (Dictyoptera: Blattellidae). *Neotrop. Entomol.* 49:275–283. https://doi.org/10.1007/s13744-019-00739-9

Buczkowski G, Schal C. 2001. Method of insecticide delivery affects horizontal transfer of fipronil in the German cockroach (Dictyoptera: Blattellidae). *J. Econ. Entomol.* 94:680–685. https://doi.org/10.1603/0022-0493-94.3.680

Cohn RD, Arbes Jr. , SJ, Jaramillo R, et al. 2006. National prevalence and exposure risk for cockroach allergen in U.S. households. *Environ. Health Perspect.* 114:522–526. https://doi.org/10.1289/ehp.8561

Davies K, Petranovic T. 1986. Survey of attitudes of apartment residents to cockroaches and cockroach control. *J. Environ. Health.* 49:85–88.

DeVries ZC, Santangelo RG, Crissman J, et al. 2019a. Exposure risks and ineffectiveness of total release foggers (TRFs) used for cockroach control in residential settings. *BMC Public Health.* 19:96. https://doi.org/10.1186/s12889-018-6371-z

DeVries ZC, Santangelo RG, Crissman J, et al. 2019b. Pervasive resistance to pyrethroids in German cockroaches (Blattodea: Ectobiidae) related to lack of efficacy of total release foggers. *J. Econ. Entomol.* 112:2295–2301. https://doi.org/10.1093/jee/toz120

Dingha B, Jackai L, Monteverdi RH, et al. 2013. Pest control practices for the German cockroach (Blattodea: Blattellidae): a survey of rural residents in North Carolina. *Fla. Entomol.* 96:1009–1015. https://doi.org/10.1653/024.096.0339

Donkor ES. 2019. Nosocomial pathogens: an in-depth analysis of the vectorial potential of cockroaches. *Trop. Med. Infect. Dis.* 4:14. https://doi.org/10.3390/tropicalmed4010014

Durier V, Rivault C. 1999. Food bait preference in German cockroach, Blattella germanica (L.) (Dictyoptera: Blattellidae). *Proceedings of the Third International Conference on Urban Pests.* p. 113–119. https://www.icup.org.uk/media/tc2dg0sh/icup403.pdf

Durier V, Rivault C. 2000. Comparisons of toxic baits for controlling the cockroach, *Blattella germanica*: attractiveness and feeding stim-

ulation. *Med. Vet. Entomol*. 14:410–418. https://doi.org/10.1046/j.1365-2915.2000.00259.x

Ebeling W, Wagner RE, Reierson DA. 1966. Influence of repellency on the efficacy of blatticides. I. Learned modification of behavior of the German cockroach. *J. Econ. Entomol*. 59:1374–1388. https://doi.org/10.1093/jee/59.6.1374

Environmental Protection Agency (EPA). 2022. *40 CFR 152.25—Exemptions for pesticides of a character not requiring FIFRA regulation*. US Environmental Protection Agency. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-E/part-152/subpart-B/section-152.25.

Gaire S, Sierras A, Morgan HL, et al. 2024. Behavioral responses of field-collected German cockroaches to pyrethroids and pyrethroid-formulated insecticides. *Pest Manag. Sci*. 80:433–441. https://doi.org/10.1002/ps.7774

González JW, Yeguerman C, Marcovecchio D, et al. 2016. Evaluation of sublethal effects of polymer-based essential oils nanoformulation on the German cockroach. *Ecotoxicol. Environ. Saf*. 130:11–18. https://doi.org/10.1016/j.ecoenv.2016.03.045

Gordon JM, Eva MJ, Gaire S, et al. 2024. Common consumer residual insecticides lack efficacy against insecticide-susceptible and resistant populations of the German cockroach (Blattodea: Ectobiidae). Rust M, editor. *J. Econ. Entomol*. 117:2051–2059. https://doi.org/10.1093/jee/toae158

Gordon JM, Sierras AJ, Jackson DV, et al. 2025. Laboratory and in-home evaluations of consumer- and professional-grade cockroach baits. *J. Econ. Entomol*. 118:826–837. https://doi.org/10.1093/jee/toae291

Gore JC, Schal C. 2004. Laboratory evaluation of boric acid-sugar solutions as baits for management of German cockroach infestations. *J. Econ. Entomol*. 97:581–587. https://doi.org/10.1603/0022-0493-97.2.581

Gruchalla RS, Pongracic J, Plaut M, et al. 2005. Inner City Asthma Study: relationships among sensitivity, allergen exposure, and asthma morbidity. *J. Allergy Clin. Immunol*. 115:478–485. https://doi.org/10.1016/j.jaci.2004.12.006

Huang K, Zhang D, Ren J-J, et al. 2020. Screening of the repellent activity of 12 essential oils against adult German cockroach (Dictyoptera: Blattellidae): preparation of a sustained release repellent agent of binary oil-γ-CD and its repellency in a small container. *J. Econ. Entomol*. 113:2171–2178. https://doi.org/10.1093/jee/toaa162

Kim J-R, Jeong I-H, Lee YS, et al. 2015. Insecticidal activity of cinnamon essential oils, constituents, and (E)- cinnamaldehyde analogues against Metcalfa pruinosa say (Hemiptera: Flatidae) nymphs and adults. *Korean J. Appl. Entomol*. 54:375–382. https://doi.org/10.5656/ksae.2015.10.0.056

Koul O, Walia S, Dhaliwal GS, et al. 2008. Essential oils as green pesticides: potential and constraints. *Biopestic. Int*. 4:63–84.

Lee C-Y, Rust MK. 2021. Chemical control methods. In: Wang C, Lee C-Y, Rust Michael K, editors. *Biology and management of the German cockroach*. CSIRO Publishing. p. 165–212.

Lee C-Y, Wang C. 2021. German cockroach infestations in the world and their social and economic impacts. In: Lee C-Y, Wang C, Rust MK, editors. *Biology and management of the German cockroach*. CSIRO Publishing. p. 1–16.

Lee S-H, Choe D-H, Rust MK, et al. 2022a. Reduced susceptibility towards commercial bait insecticides in field German cockroach (Blattodea: Ectobiidae) populations from California. *J. Econ. Entomol*. 115:259–265. https://doi.org/10.1093/jee/toab244

Lee S-H, Choe D-H, Scharf ME, et al. 2022b. Combined metabolic and target-site resistance mechanisms confer fipronil and deltamethrin resistance in field-collected German cockroaches (Blattodea: Ectobiidae). *Pestic. Biochem. Physiol*. 184:105123. https://doi.org/10.1016/j.pestbp.2022.105123

Lee S-H, So J, Kund G, et al. 2024. Toxicity of isocycloseram, an isoxazoline insecticide, against laboratory and field-collected German cockroaches (Blattodea: Ectobiidae). *J. Econ. Entomol*. 117:1086–1094. https://doi.org/10.1093/jee/toae079

Matsuo N. 2019. Discovery and development of pyrethroid insecticides. *Proc. Jpn. Acad. Ser. B Phys. Biol. Sci*. 95:378–400. https://doi.org/10.2183/pjab.95.027

Miller DM, Black JB, Wang C. 2021. Management in multi-unit dwellings and commercial kitchens. In: Wang C, Lee C-Y, Rust M, editors. *Biology and management of the German cockroach*. CSIRO Publishing. p. 269–298.

Miller DM, Meek F. 2004. Cost and efficacy comparison of integrated pest management strategies with monthly spray insecticide applications for German cockroach (Dictyoptera: Blattellidae) control in public housing. *J. Econ. Entomol*. 97:559–569. https://doi.org/10.1093/JEE/97.2.559

Miller DM, Smith EP. 2020. Quantifying the efficacy of an assessment-based pest management (APM) program for German cockroach (L.) (Blattodea: Blattellidae) control in low-income public housing units. *J. Econ. Entomol*. 113:375–384. https://doi.org/10.1093/jee/toz302

Mota-Sanchez D, Wise JC. 2024. *Blattella germanica. Arthropod pesticide resistance database*. https://www.pesticideresistance.org/

Nalyanya G, Liang D, Kopanic Jr. , RJ, et al. 2001. Attractiveness of insecticide baits for cockroach control (Dictyoptera: Blattellidae): laboratory and field studies. *J. Econ. Entomol*. 94:686–693. https://doi.org/10.1603/0022-0493-94.3.686

Oladipupo SO, Hu XP, Appel AG. 2022. Essential oils in urban insect management – a review. *J. Econ. Entomol*. 115:1375–1408. https://doi.org/10.1093/jee/toac083

Organisation for Economic Co-operation and Development (OECD). 2013. *Guidance document on assays for testing the efficacy of baits against cockroaches*. OECD Publishing. https://doi.org/10.1787/6661a35c-en.

Phillips AK, Appel AG, Sims SR. 2010. Topical toxicity of essential oils to the German cockroach (Dictyoptera: Blattellidae). *J. Econ. Entomol*. 103:448–459. https://doi.org/10.1603/EC09192

Reierson DA. 1995. Baits for German cockroach control. In: Rust MK, Owens JM, Reierson DA , editors. *Understanding and controlling the German cockroach*. Oxford University Press. p. 231–265.

Rosenstreich DL, Eggleston P, Kattan M, et al. 1997. The role of cockroach allergy and exposure to cockroach allergen in causing morbidity among inner-city children with asthma. *N Engl. J. Med*. 336:1356–1363. https://doi.org/10.1056/NEJM199705083361904

Rust MK, Appel AG, Lee S-H, et al. 2022. Impact of sprays on baits in controlling German cockroaches, *Blattella germanica*. In: Bueno-Marí R, Montalvo T, Robinson WH, editors. *Proceedings of the tenth international conference of urban pests*. p. 148–151.

Rust MK, Reierson DA. 1978. Comparison of the laboratory and field efficacy of insecticides used for German cockroach Control1. *J. Econ. Entomol*. 71:704–708. https://doi.org/10.1093/jee/71.4.704

Rust MK, Reierson DA, Zeichner BC. 1993. Relationship between insecticide resistance and performance in choice tests of field-collected German cockroaches (Dictyoptera: Blattellidae). *J. Econ. Entomol*. 86:1124–1130. https://doi.org/10.1093/jee/86.4.1124

Schal C, DeVries ZC. 2021. Public health and veterinary importance. In: Wang C, Lee C-Y, Rust MK, editors. *Biology and management of the German cockroach*. CSIRO Publishing. p. 17–52.

Scharf ME, Gondhalekar AD. 2021. Insecticide resistance: perspectives on evolution, monitoring, mechanisms and management. In: Wang C, Lee C-Y, Rust MK, editors. *Biology and management of the German cockroach*. CSIRO Publishing. p. 231–255.

Sims SR, Appel AG, Eva MJ. 2010. Comparative toxicity and repellency of microencapsulated and other liquid insecticide formulations to the German cockroach (Dictyoptera: Blattellidae). *J. Econ. Entomol*. 103:2118–2125. https://doi.org/10.1603/ec09415

Strong CA, Koehler PG, Patterson RS. 1993. Oral toxicity and repellency of borates to German cockroaches (Dictyoptera: Blattellidae). *J. Econ. Entomol.* 86:1458–1463. https://doi.org/10.1093/jee/86.5.1458

Wagner RE, Ebeling W, Clark WR. 1964. An electric barrier for confining cockroaches in large rearing or field collecting cans. *J. Econ. Entomol.* 57:1007–1009. https://doi.org/10.1093/jee/57.6.1007

Wang C, Abou El-Nour MM, Bennett GW. 2008. Survey of pest infestation, asthma, and allergy in low-income housing. *J. Community Health*. 33:31–39. https://doi.org/10.1007/s10900-007-9064-6

Wang C, Bischoff E, Eiden AL, et al. 2019. Residents attitudes and home sanitation predict presence of German cockroaches (Blattodea: Ectobiidae) in apartments for low-income senior residents. *J. Econ. Entomol.* 112:284–289. https://doi.org/10.1093/jee/toy307

Wickham JC, Chadwick PR, Stewart DC. 1974. Factors which influence the knockdown effect of insecticide products. *Pestic. Sci.* 5:657–664. https://doi.org/10.1002/ps.2780050518

Yoon C, Kang S-H, Yang J-O, et al. 2009. Repellent activity of citrus oils against the cockroaches *Blattella germanica*, *Periplaneta americana* and *P. fuliginosa*. *J. Pestic. Sci*. 34:77–88. https://doi.org/10.1584/jpestics.G07-30

Yu SJ. 2014. *The toxicology and biochemistry of insecticides*. 2nd ed. CRC Press. 380 p.