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Laboratory and in-home evaluations of consumer- and professional-grade cockroach baits

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German cockroaches (*Blattella germanica* (L.)) are a persistent pest in affordable housing and studies indicate that residents implement control on their own to deal with cockroaches within their homes. While many do-it-yourself (DIY) control options have proven ineffective, baits are widely considered to be a viable DIY solution for residents who do not have access to professional pest control services. To evaluate their efficacy, we tested consumer-use baits (Combat gel bait, Combat bait stations, and Hot Shot liquid bait stations) in both laboratory two-choice assays and in-home assays, comparing them with professional gel baits (Vendetta Nitro, Advion Evolution, and Maxforce FC Magnum). All baits (consumer- and professional-grade) caused > 80% mortality within 14 d in laboratory assays, including against home-collected German cockroach populations. However, the in-home efficacy of consumer-grade baits in comparison to their performance in laboratory assays was inconsistent, with some baits resulting in significant declines in trap catch in 1 month (Hot Shot liquid bait stations), some taking longer (Combat gel bait), and some never showing a decline (Combat bait stations). Discrepancies between product performance in laboratory and in-home studies are concerning and suggest that laboratory assays alone might not be indicative of the potential for control, especially in the context of the more complex home environment. Failures of consumer-grade baits may require re-evaluation of current recommendations for the use of consumer-grade cockroach baits as a viable control option for residents struggling with cockroach infestations without access to professional pest management.

Key words: cockroach control, *Blattella germanica*, insecticidal bait

Introduction

German cockroaches (*Blattella germanica* (L.)) are a major threat to human health, largely due to their roles in asthma development and exacerbation (Bernton and Brown 1964, Chapmen et al. 1996, Rosenstreich et al. 1997, Eggleston et al. 1998, Arruda et al. 2001, Arruda 2005, Gore and Schal 2007, Pomés et al. 2007), potential for pathogen transmission (Fakoorziba et al. 2010, Menasria et al. 2014, Turner et al. 2022), and the severe impacts on overall quality of life for those living with chronic infestations. Their short life cycle and documented resistance to many insecticides make them challenging pests to control (Rust 1995, Wang et al. 2021). In particular, German cockroaches have demonstrated high levels of resistance to pyrethroids (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. 2022b, Gordon et al. 2024), common active ingredients in liquid residual products. In contrast to liquid residual products, cockroach gel baits provide residual efficacy through a toxicant in a food matrix that may also contain additional attractants/phagostimulants. Gel bait formulations are designed to be applied as small placements on surfaces and in cracks and crevices close to cockroach aggregation sites, reducing the amount of active ingredient (AI) applied in structures compared to liquid residual formulations (Appel and Rust 2021). Despite the proven success of professional gel baits (Appel 1992, Anikwe et al. 2014, DeVries et al. 2019a, Miller and Smith 2020), integrated pest management (IPM) programs utilizing baits are often lacking in affordable housing, resulting in persistent German cockroach infestations in homes (Wang et al. 2019a). The lack of IPM adoption in affordable housing

is likely due to cost, with direct comparisons of the overall expenses of IPM versus traditional residual spray applications finding IPM-based treatments to be around 3 times more expensive (Miller and Meek 2004, Shahraki et al. 2011).

The responsibility for pest control in affordable housing often lies with property management and housing authorities, who submit requests for pest control bids (Miller et al. 2021). The United States Department of Housing and Urban Development (HUD) stipulates that the lowest "responsible" bidder be awarded the contract for HUD-subsidized housing, but a lack of clear definition for what constitutes "responsible" often results in pest control contracts being awarded based on cost alone (Miller and Meek 2004, Wang and Bennett 2009, Miller et al. 2021). As a result, residents of multi-family and public housing have a higher likelihood of experiencing cockroach infestations (Milstead et al. 2006, Northridge et al. 2010), as well as associated health impacts of cockroach allergen exposure such as asthma (Cohn et al. 2006). Consequently, many residents lack faith in the ability of pest control to eradicate cockroaches (Wood et al. 1981, Davies and Petranovic 1986), and many turn to products available to them that promise to control cockroaches.

The efficacy of current consumer-grade cockroach baits has been evaluated in laboratory studies (Appel 1990, 1992, El-Monairy et al. 2015, Lucero 2023), but when it comes to performance in homes, where competitive food sources and extensive harborage locations may exist, testing has been limited.

Across the board, resources and extension materials written for residents looking to control cockroaches highlight the efficacy of baits and recommend them for use (Potter 2018, Layton and Goddard 2019, Ogg and Ogg 2019, Sutherland et al. 2019, Koehler et al. 2022). Given the lack of empirical evidence on the efficacy of current consumer cockroach bait products in the home environment, there is a need to determine if these products provide effective cockroach control in the home comparable to laboratory efficacy. Our study represents an assessment of consumer bait products that are marketed for cockroach control. We conducted laboratory and in-home evaluations of consumer gel baits, gel bait stations, and liquid bait stations from various manufacturers. Two-choice laboratory assays evaluated survival probability and survival time for susceptible and home-collected populations of *B. germanica*, including populations collected from sites in our concurrent in-home study. The in-home study evaluated cockroach trap catch within homes following treatment with consumer bait products. In addition to assessing the performance of consumer bait products, the accuracy of laboratory bait evaluations in predicting in-home performance is also discussed.

Materials and Methods

Study Insects

Nine populations of *B. germanica* were tested in laboratory evaluations of bait products. Orlando Normal (ON) is an insecticide-susceptible laboratory population, originally collected in Orlando, Florida, USA in the mid-1940s (Koehler and Patterson 1986). Eight populations (220-24, 220-7, 225-66, 225-9, 250-60, 250-62, 250-90, 250-43) were collected from individual apartments from a housing complex in Winchester, Kentucky, USA between October 2021 and February 2022. These homes were enrolled in the in-home study and cockroaches were collected prior to study treatment. All populations were reared at 25°C, 50% RH, and under a 12:12 h (L:D) photoperiod cycle and provided with water and food (Mazuri Rat & Mouse Diet, Mazuri Exotic Animal Nutrition, St Louis, MO, USA) ad libitum, and displayed varying levels of resistance to pyrethroid (cypermethrin) and neonicotinoid (dinotefuran) insecticides (ZCD, unpublished data).

Consumer and Professional-grade Bait Products

Six bait products were evaluated in our study. Three consumer-grade products were evaluated in in-home and laboratory studies: Combat Max Roach Killing Gel (0.01% Fipronil; Combat Insect Control Systems, Henkel Corporation, Rocky Hill, Connecticut, USA), Combat Roach Killing Bait Stations (0.05% Fipronil; Combat Insect Control Systems, Rocky Hill, Connecticut, USA), and Hot Shot Liquid Roach Bait stations (0.05% Dinotefuran; Spectrum Group, Division of United Industries Corporation, St. Louis, Missouri, USA). Consumer-grade products were selected based on consumer bait products observed at retailers and in homes (personal observations made by JMG, AJS, and ZCD) and availability at large retail stores. Three professional bait products were used to provide positive controls/method validation for gel bait efficacy: Vendetta Nitro (0.50% Clothianidin, 0.50% Pyriproxyfen, Mclaughlin Gormley King Company (MGK), Minneapolis, Minnesota, USA), Advion Evolution (0.60% Indoxacarb, Syngenta Corp Protection, LLC, Greensboro, North Carolina, USA), and Maxforce FC Magnum (0.05% Fipronil, Envu (formerly Bayer Environmental Science), Cary, North Carolina, USA). Professional products were evaluated separately (laboratory assays) and in a staggered application (in-home study). This staggered application protocol was developed based on previous literature that evaluated the application of multiple professional cockroach gel bait products (Sever et al. 2007, Wang and Bennett 2009, Miller and Smith 2020). Treatment with professional products was included as a treatment group to demonstrate the ability for cockroaches to be eliminated/reduced with the correct products.

Laboratory Evaluation of Bait Products

We evaluated bait efficacy in the laboratory using the susceptible population (ON) and all 8 home-collected populations in two-choice assays. To allow populations collected from homes during our in-home study to grow to sufficient numbers, laboratory assays were conducted between July 2023 and December 2023. From each population, male cockroaches ($n = 20$) were randomly selected from laboratory colonies and were acclimated to test arenas (29.9 × 15.2 × 10.8 cm; Model: 1851-80, Sterlite Corporation, Townsend, MA, USA) for 24 h, with water and corrugated cardboard harborage but no food. After 24 h, arenas were provisioned with a standard laboratory diet (Mazuri Rat & Mouse Diet) as well as 1 of the 6 bait products.

In the laboratory assay, all 3 professional gel bait products were evaluated separately, as individual treatments. Each gel bait product (Vendetta Nitro, Advion Evolution, and Maxforce FC Magnum gel baits and the consumer gel bait product, Combat Max Roach Killing Gel) was applied to a small plastic lid (4.9 × 0.6 cm, polyethylene terephthalate, Item #: 127PL100, Webstaurantstore.com, USA) as a single 500 mg bait application. This quantity ensured sufficient bait was available for the duration of the 28 d assay. Containerized bait products were applied individually into arenas (e.g., one single Combat station or one single Hot Shot station). Controls were set up identically to treatment replicates, except no bait was applied into the arena. Baits were available for the duration of the assay and dead cockroaches were not removed from arenas for the duration of the assays. Mortality was defined as the inability of the insect to right itself or make coordinated movement and was evaluated every

day for 7 d, and again at 14 d, 21 d, and 28 d. Three replicates were performed for each product and each population. The laboratory study design utilized a smaller arena than current EPA laboratory testing guidelines (EPA 2019) for cockroach bait products and only male cockroaches as a best-case scenario for product efficacy (i.e., higher likelihood of bait interception and a physiologically stable life stage that feeds regularly).

In-home Evaluation of Bait Products

Concurrent with laboratory studies, baits were evaluated in the homes of voluntary study participants. In-home evaluations of baits took place from 8 July 2021 to 11 January 2024. All participant recruitment was performed under institutional review board (IRB) approval through the University of Kentucky (Protocol #: 67961). Recruitment was conducted by referrals to general locations having problems with cockroaches by local civic departments, including fire services and code enforcement, in the cities of Lexington and Winchester, Kentucky, USA. Information regarding specific complexes facing persistent cockroach problems was collected and the study team conducted random recruitment within these locations.

With informed consent obtained, 32 homes were enrolled in our study. These homes were all single apartments, ranging from one to 3 bedrooms (estimated 700–1,100 ft^2), within privately owned multi-family apartment buildings, which ranged from 2 to 3 stories. Individual homes were involved in the study for a total of 5 months which included 5 paired home visits. Paired home visits encompassed trap set and trap collection 1 wk apart, with treatment applied following trap collection where applicable (Fig. 1). Due to ethical concerns of leaving residents without relief from cockroach infestation for the entirety of the study, we used an embedded-control study design, similar to internal controls in Dingha et al. (2016). The initial visit represented an initial survey of cockroach infestation levels in each home. Cockroach populations were evaluated again after 1 mo through a 1-wk trapping period at Month 0/Baseline. If trap counts indicated a sustained or increasing population within the home (≥70% of initial trap count), treatment was applied. The 1-mo period between the initial visit and the Month 0/baseline visit represented the "control" period for that home. Additional paired visits took place at 2 wk, 1 mo, 2 mo, and 4 mo post-treatment. The treatment schedule was designed to optimize bait efficacy, with treatments being applied every 2–4 wk until the final gap between Month 2 and Month 4 (Appel and Rust 2021). For each cockroach trapping event, 4 glue traps (Victor Roach pheromone sticky traps Model M330, Woodstream, Lititz, Pennsylvania, USA) were placed throughout the kitchen, along vertical edges (e.g., side of cabinets, the wall) to maximize cockroach catch. Efforts were made to place traps in proximity to the refrigerator, underneath the kitchen sink, and in cabinets with signs of cockroach activity, when possible. Within each apartment, for all subsequent trapping events, traps were placed in the same locations established at the initial trap set (Timepoint –1) for the duration of the study.

Once the cockroach population in the home was confirmed to be stable or increasing (≥70% of initial trap catch at Month 0/Baseline Visit), homes were randomly assigned one of the 4 bait treatment groups: Hot Shot liquid bait stations, Combat bait stations, Combat gel bait, or a staggered application of professional gel bait products (positive control, representing a best-case scenario for cockroach population reduction, given the application of multiple products, with different formulations and active ingredients with different modes of action). The use of professional bait products was used as a method validation step, to exclude application proficiency as a variable in bait failure, thus isolating the products being evaluated. Bait application was focused in the kitchen and bathroom(s), with other areas of the home treated based on observed need or resident request. For consumer bait products, bait stations were placed according to label instructions, with an entire package of Hot Shot liquid bait stations (6) and Combat bait stations (18) placed in the kitchen (underneath/next to the stove and refrigerator and other large appliances, behind smaller appliances on countertops, inside of cabinets, etc.) and/or bathroom (e.g., inside of cabinets, behind the toilet) and replenished at each subsequent treatment timepoint to ensure bait was available. Combat gel bait was also placed according to label instructions, in "numerous dime-sized applications." For each home assigned the professional gel bait treatment, product

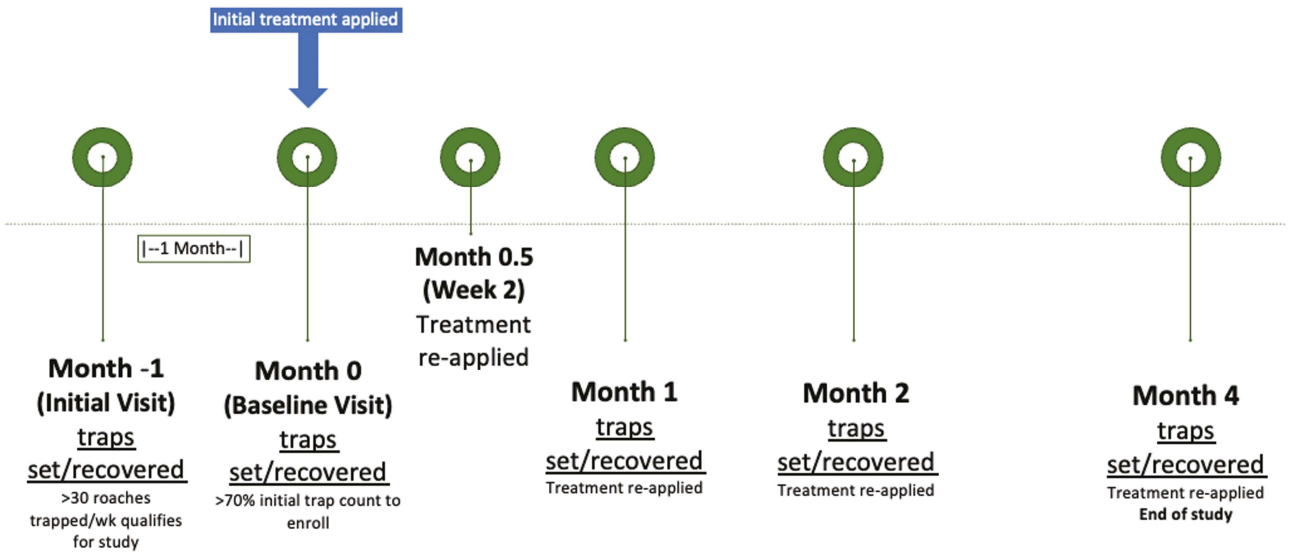

Fig. 1. Study timeline of bait evaluations within homes. The study spanned 5 mo with a control period (Initial visit to Month 0/Baseline) to confirm whether cockroach populations within homes were stable or growing. Traps were set to assess cockroach population at the Initial visit, Month 0/Baseline, Month 1, Month 2, and Month 4. Traps remained for 1 wk within the home before being collected and mean cockroaches/day determined. Bait treatments were applied at Month 0/Baseline, week 2 (follow-up), Month 1, and Month 2.

application was staggered, starting with Vendetta Nitro at Timepoint 0, Advion Evolution at Timepoint 0.5 (as needed), Maxforce FC Magnum at Timepoint 1, and Vendetta Nitro again at Timepoint 2. Visits at Timepoint 0.5 represented a "check-in" with residents and a visual evaluation of bait consumption, in which bait was applied as needed at the discretion of the study team, and 9/15 homes received a bait application at this time point. All consumer and professional gel baits were applied in small bait "dots" (~pea-sized) throughout the home, with a focus on areas in the kitchen and bathroom with signs of cockroach activity (e.g., inside of cabinets, behind the larger appliances such as the refrigerator and stove, etc.). The total bait applied for each visit was measured using differences in bait tube weight before and after bait application. Upon completion of the study, homes with remaining cockroaches were provided with a thorough application of professional bait products by the study team. Cockroach traps were brought back to the lab, frozen, and enumerated.

Statistical Analyses

Kaplan–Meier analysis (Kaplan and Meier 1958) was used to analyze the impact of bait products on survival by cockroach population in laboratory assays. Within each population, all treatments (6 products and no-bait control) were compared, and log-rank tests were used to determine differences between survivorship probabilities of all treatments for that population. Lack of variation (i.e., 100% mortality by Day 1) drove singularity issues in the insecticide-susceptible ON population. Therefore, ON was excluded from post-hoc testing. Kaplan–Meier survival analysis was also used to compare the effect of population on survival within each treatment. Log-rank tests were used to determine differences between survivorship probabilities for all populations within each treatment. Finally, average percent mortality at 2 d, 14 d, and 28 d was calculated and compared across products at all 3 time points using analysis of variance (ANOVA) with Tukey's honestly significant difference (HSD) test to assess overall differences between mean percent survival of home-collected populations for each product. Data were confirmed to meet all assumptions. Control mortality across all laboratory assays was < 20% and was used to correct mortality data for products using the Henderson–Tilton equation (Henderson and Tilton 1955).

For the in-home study, data were square-root transformed to meet the assumptions of normality. Repeated measures data were fit to a linear mixed effects model and ANOVA was used to compare mean cockroaches/day between time points (months) for each product. Tukey's HSD test was used to assess pairwise differences between time points (months). Data were confirmed to meet all assumptions. All analyses were conducted in R version 2023.09.0 + 463 (R Development Core Team 2023) and visualizations were created using the ggplot2 package (v3.4.3; Wickham 2016).

Results

Laboratory Evaluation of Bait Products

When survivorship was analyzed by population, for all populations, treatment had a significant effect on survival probability, with significant differences between all bait products and the untreated control (220-24: $\chi^2 = 221.0$, df = 6, $P < 0.001$; 220-7: $\chi^2 = 199.0$, df = 6, $P < 0.001$; 225-66: $\chi^2 = 252.0$, df = 6, $P < 0.001$; 225-9: $\chi^2 = 230.0$, df = 6, $P < 0.001$; 250-43: $\chi^2 = 274.0$, df = 6, $P < 0.001$; 250-60: $\chi^2 = 265.0$, df = 6, $P < 0.001$; 250-62: $\chi^2 = 250.0$, df = 6, $P < 0.001$; 250-90: $\chi^2 = 266.0$, df = 6, $P < 0.001$; ON: $\chi^2 = 396.0$, df = 6, $P < 0.001$).

When survivorship was analyzed by treatment, the population had a significant effect on survival time (Combat bait stations: $\chi^2 = 122.0$, df = 8, $P < 0.001$; Hot Shot liquid bait stations: $\chi^2 = 16.5$, df = 8, $P = 0.04$; Combat gel bait: $\chi^2 = 122.0$, df = 8, $P < 0.001$; Vendetta Nitro: $\chi^2 = 35.2$, df = 8, $P < 0.001$; Advion Evolution gel bait: $\chi^2 = 124$, df = 8, $P < 0.001$; Maxforce FC Magnum gel bait: $\chi^2 = 99$, df = 8, $P < 0.001$; Fig. 2, Table S1). For all products, home-collected populations survived significantly longer than the ON laboratory susceptible population, except Vendetta Nitro gel bait (no significant difference between ON and 220-24) and Hot Shot Liquid bait stations (ON only significantly different from 220-7).

There was considerable variability in average percent mortality between products at 2 d (~54%–95%), with significantly higher mortality from Hot Shot Liquid bait stations than all other consumer- and professional-grade bait products evaluated, while the remaining products had strong overlap in percent mortality ($F = 8.93$; df = 5, 42; $P < 0.001$; Fig. 3A). At 14 d, average percent mortality with Hot Shot Liquid bait stations was 100% across all replicates, and only significantly differed from Combat bait stations and Vendetta Nitro gel bait and did not differ from Combat, Maxforce FC Magnum, or Advion Evolution gel baits ($F = 6.52$; df = 5, 42; $P < 0.001$; Fig. 3B). At 28 d, only Combat bait stations significantly differed from the other products, showing a significantly lower percent mortality compared to all other products (84.8% ± 4.0%; $F = 6.84$; df = 5, 42; $P < 0.001$; Fig. 3C). However, all other products did not significantly differ from one another and had an average percent mortality of at least 93%.

In-home evaluation of bait products

During the study, gel bait (either Combat or the staggered application of professional gel bait products [Vendetta Nitro, Advion Evolution, Maxforce FC Magnum]) was applied at the following mean ± SEM rates: ~41 ± 5 g gel bait were applied at Month 0, ~39 ± 5 g at Month 1, and ~33 ± 7 g at Month 2, for an average total of ~107 ± 10 g of bait applied in each home for the duration of the study. For homes that had additional bait applied at Week 2, 13 ± 3 g of gel bait was applied. Mean cockroaches per day significantly differed between time points for both the professional bait product treatment ($F = 25.51$; df = 3, 17; $P = < 0.001$) (Fig. 4A) and the Hot Shot liquid bait stations ($F = 7.70$; df = 3, 15; $P = < 0.001$) (Fig. 4B), in which mean cockroaches trapped per day was significantly lower at Month 1, Month 2, and Month 4 than they were at Month 0/Baseline. For Combat gel bait, mean cockroaches/day was significantly different between time points ($F = 13.44$; df = 3, 26; $P = 0.002$), with Month 0/Baseline significantly different from Month 2 and Month 4, but not significantly differing from Month 1 (Fig. 4C). Mean cockroaches trapped at Month 1 and Month 2 did not significantly differ but were significantly higher at Month 2 than Month 4. Finally, there were no significant differences between time points in homes treated with Combat bait stations ($F = 2.08$; df = 3, 15; $P = 0.139$) (Fig. 4D).

Cost Analysis

The cost of Combat gel bait treatment was the lowest of the consumer or professional products used in our in-home study (realized cost of ~$18.19 USD, Table 1). Combat bait stations and Hot Shot liquid bait stations had similar realized costs ($31.47 and $31.44, across the duration of the study), and treatment with professional products had the highest cost, with an applied materials cost of ~$40.91, but due to the need to round up in tubes of bait and purchase packages of 4 for Vendetta Nitro and Advion Evolution, had a realized cost of $114.35 (Table 1).

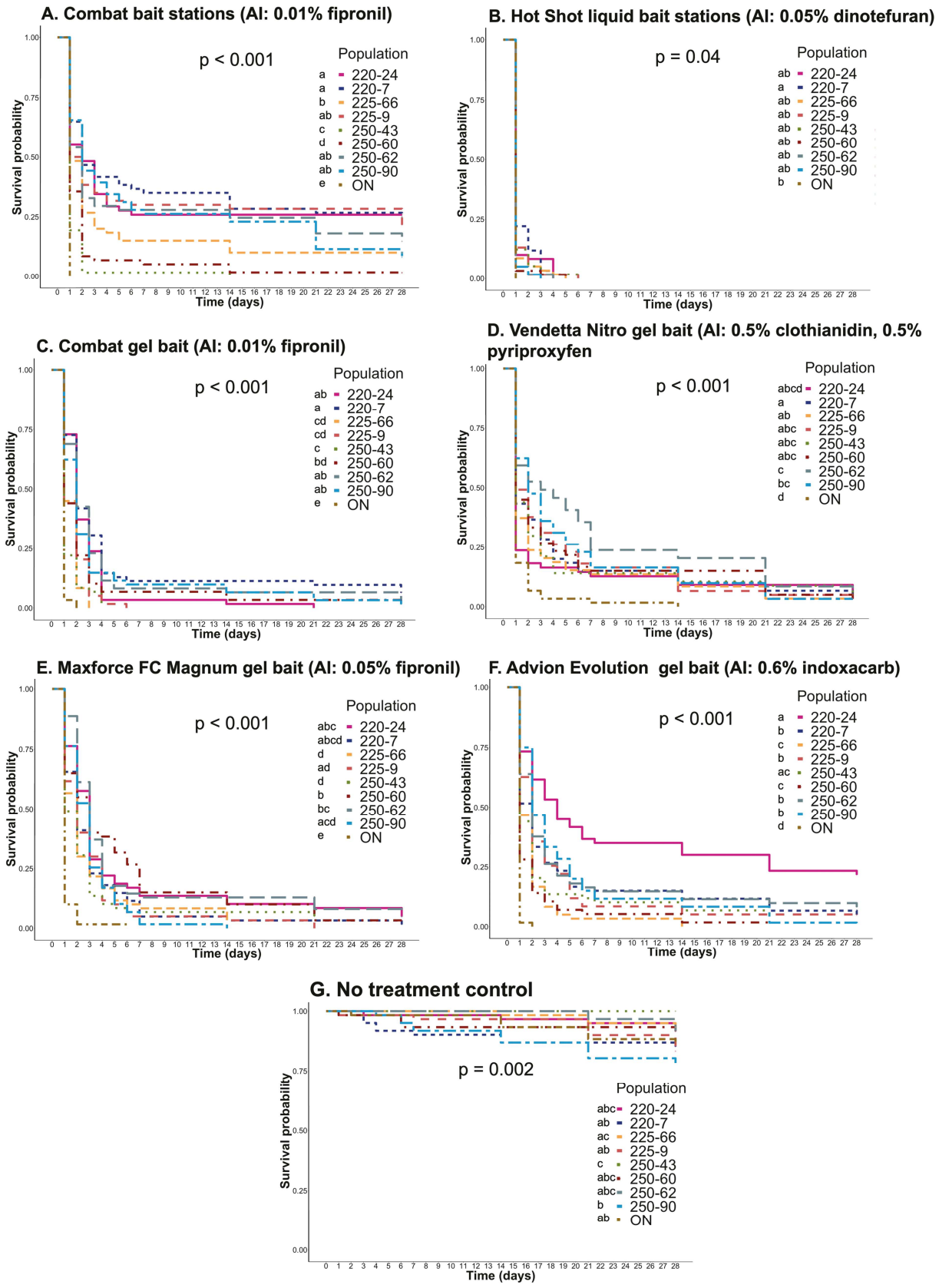

Fig. 2. Kaplan–Meier survival curves for consumer and professional cockroach baits against 8 home-collected German cockroach (*Blattella germanica*) populations and one susceptible population (ON) in two-choice laboratory assays. Differences in lowercase letters next to the population name in each figure legend represent significant differences among populations for each product based on Kaplan–Meier survival analysis followed by a log-rank test. Control mortality did not exceed 20% in any controls (panel G).

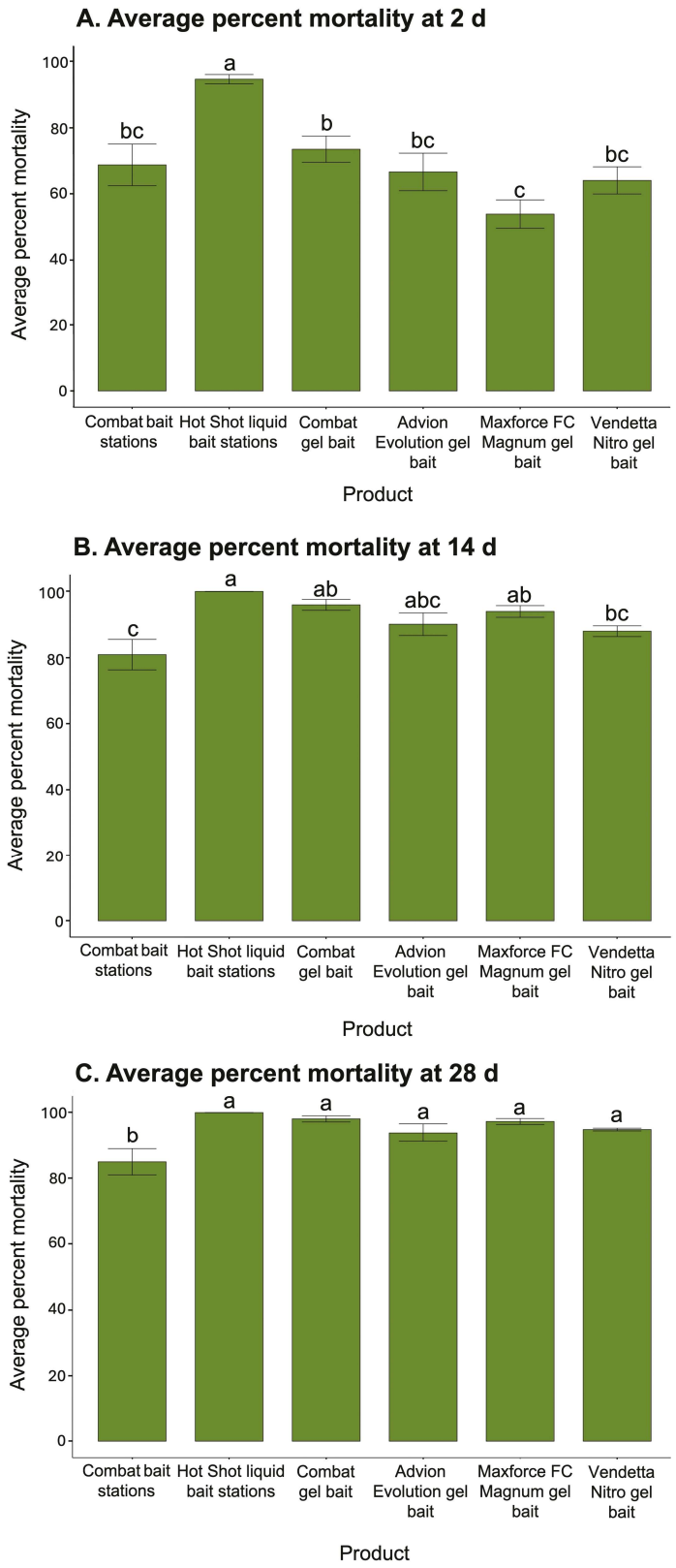

Fig. 3. Average percent mortality across 8 home-collected German cockroach populations from consumer- and professional-grade cockroach bait products after (A) 2 d, (B) 14 d, and (C) 28 d in laboratory two-choice assays. Differences in lowercase letters in each graph represent significant differences among products for each time point (ANOVA, followed by Tukey's HSD [honestly significant difference] test; $P < 0.05$).

Discussion

In small-scale laboratory evaluations, with male cockroaches only, all consumer- and professional-grade baits caused at least 80% mortality for all populations and products tested after 28 d. However, there was considerable variability between products, and between populations within each product. As expected, ON consistently

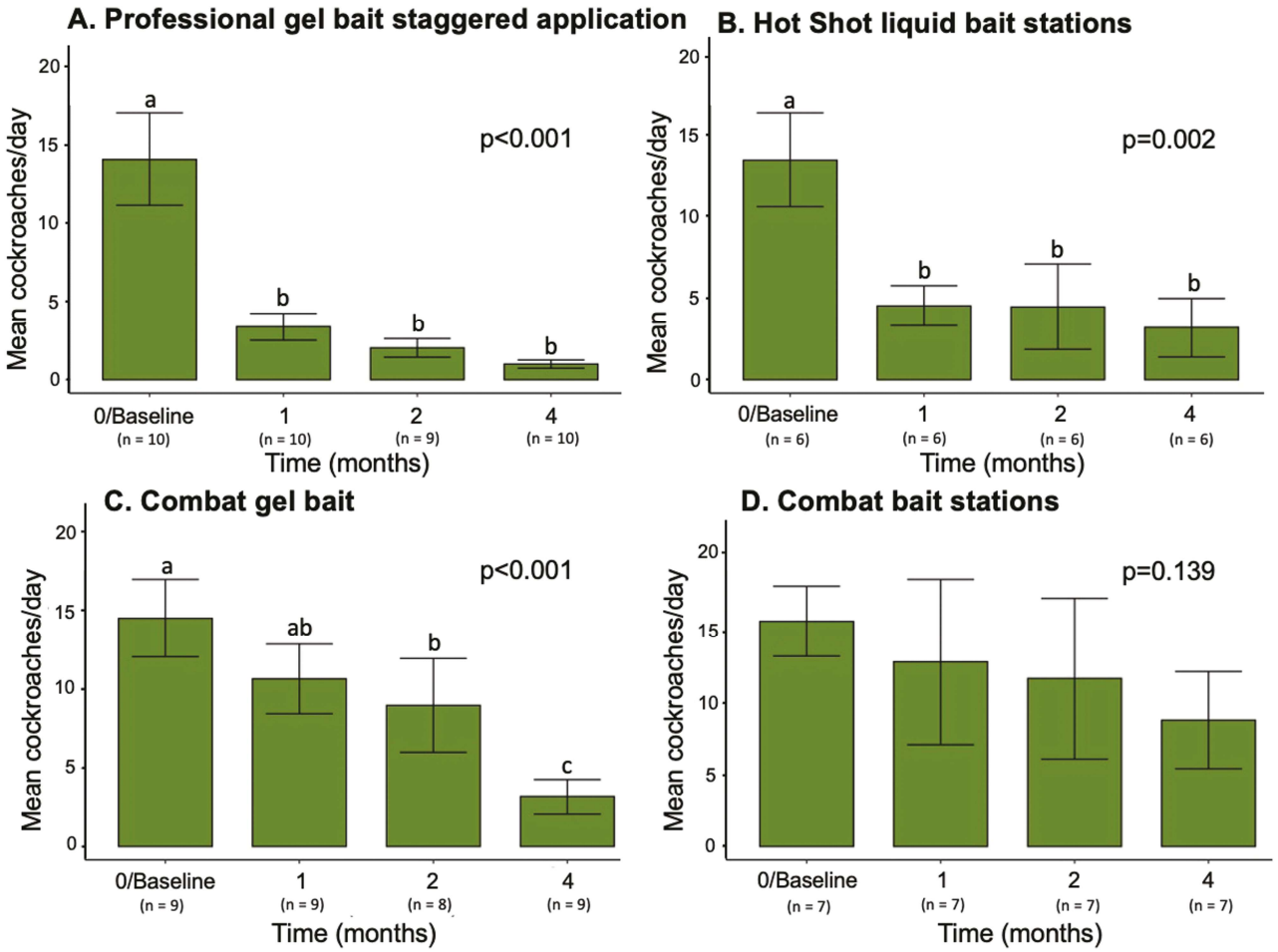

Fig. 4. Mean trap catch (cockroaches per day) at each sampling time point (in months) for homes treated with (A) a staggered application of professional gel bait products (Vendetta Nitro gel bait, Advion Evolution gel bait, Maxforce FC Magnum gel bait), (B) Hot Shot liquid bait stations, (C) Combat gel bait, and (D) Combat bait stations. Error bars represent the standard error of the mean (SEM). Treatment was applied in homes following the Month 0/Baseline timepoint. Differences between lowercase letters represent significant differences in cockroaches trapped between sampling time points for each product (ANOVA, followed by Tukey's HSD [honestly significant difference] test; $P < 0.05$).

showed high susceptibility to all bait products, but home-collected populations had varying responses depending on the product being tested (Supplementary Table 1, Fig. 2). Across nearly all within-product comparisons, home-collected populations had significantly higher survivorship (e.g., lower mortality) than the ON population, which confirms that these products are effective against a susceptible population. The lack of differences between ON and 220-24 with Vendetta Nitro gel bait may suggest greater susceptibility of the 220-24 population to 0.5% clothianidin and 0.5% pyriproxyfen compared to other home-collected populations. One of the AIs in Vendetta Nitro, pyriproxyfen, is an insect growth regulator, and thus does not target adult life stages, which may have limited its activity in these laboratory tests assays compared to population control in the in-home study. The lack of significant differences between ON and all populations (except 220-7) with Hot Shot liquid bait stations, suggests higher susceptibility of the majority of populations to Hot Shot liquid bait stations. When we evaluated based on population, there were significant differences between products, with the no-treatment controls having significantly higher survival than any bait product, confirming that the baits we evaluated were generally effective against German cockroaches, in the laboratory.

When considering the consumer-grade baits tested in the laboratory, Combat bait stations performed comparatively poorly, especially given the optimal conditions (bait proximity and simplified foraging environment) for bait success within laboratory assays. In contrast, both Combat gel bait and Hot Shot liquid bait stations performed significantly better, and all populations provided with liquid bait stations in laboratory assays reached 100% mortality within 1 wk, with most individuals dead after ~24 h (Fig. 2). Additionally, mortality did not differ between the susceptible population and recently collected populations from homes (Fig. 2), suggesting either a lack of resistance to the active ingredient in the Hot Shot liquid bait stations (AI: dinotefuran) or success based in the formulation itself. It should be noted that, as of November 2024, this remains the only cockroach liquid bait available for purchase/use. Given how quickly study insects died when treated with liquid bait stations in laboratory assays, further investigation should be done with a more refined timescale to assess time–mortality response between 0 and 24 h. Further studies evaluating liquid bait consumption (or the potential of mortality resulting from contact rather than ingestion of the liquid bait) and horizontal transfer of the toxicant should be done.

When considering the professional-grade baits tested, there were no major differences between any of the gel baits evaluated, and all 3 products induced > 93% mortality by 28 d. When we compare our results with those recently reported by Lee et al. (2022a), we see similar survival probabilities at 14 d for those tested with Advion

Table 1. Costs associated with the use of consumer and professional cockroach bait products

	Product	Product cost (USD)	Units per package	Mean (± SEM) product applied	Applied material cost (USD)	Total realized material cost (USD)[a]
	Combat gel bait	9.84	1	1.9 tubes	18.30	19.68
	Combat bait stations	10.49	18	54 stations	31.47	31.47
	Hot Shot liquid bait stations	10.48	6	18 stations	31.44	31.44
Professional Treatment	Vendetta Nitro	42.95	4	1.5 tubes	16.54	42.95
	Advion Evolution	37.50	4	0.6 tube	5.72	37.50
	Maxforce FC Magnum	16.95	1	1.1 tubes	18.65	33.90
	Total Professional Treatment				40.91	114.35

[a]Average total product applied/units per package (rounded to the nearest whole number), multiplied by product cost.

Evolution (Fig. 2). However, survival probabilities at 14 d for all populations treated with Maxforce FC Magnum in our study were under 18% (range: ~0–18%), which is lower than what was found by Lee et al (2022a), who reported survivorship ≥ 25% (range: ~25–50%) for the home-collected populations they tested. As these home-collected populations were collected from different buildings, discrepancies in the efficacy of products are likely due to differences in pesticide exposure and resistance development between the populations tested in the respective studies. It is possible, with continued pesticide pressure, that the populations we evaluated would experience similar reduced efficacy of products. However, resistance to fipronil in German cockroaches does not appear to develop to the same levels seen in other insecticides (González-Morales et al. 2022).

In in-home evaluations of bait products, with mixed-sex and mixed-age populations and competitive food/water sources, the success of treatments in reducing cockroach populations within the home was varied. As expected, the professional bait application (Vendetta Nitro and Advion Evolution at Month 1) as a positive control of effective treatment significantly decreased cockroaches trapped within 1 month (Fig. 4A). This is expected, given previous studies demonstrating professional insecticide gel baits to be effective at controlling cockroaches (Appel 1992, Anikwe et al. 2014, DeVries et al. 2019a, Miller and Smith 2020) and their success in our paired laboratory study (Fig. 2D, 2E, 2F).

When evaluating the consumer-grade baits, the results of the in-home study largely align with the efficacy of each product in laboratory evaluations. Consistent with their performance in the laboratory, Hot Shot liquid bait stations were the only consumer-grade product we tested that was comparable to the professional product treatments in terms of decrease in mean cockroaches trapped per day (Fig. 2B, Fig. 4B). While the total cost of consumer baits differ from professional treatments in the lack of associated labor costs, it is worth noting that a product with a single active ingredient, with 6 containerized applications in the kitchen and bathroom of a home, had comparable efficacy to applications of multiple professional gel baits, all with different active ingredients, applied as hundreds of targeted bait dots. Future studies with increased sample size should be done to evaluate the potential of liquid bait stations as a more sustainable and economically viable solution to cockroach problems in affordable housing. Also consistent with their performance in the laboratory, Combat bait stations failed to significantly reduce cockroach populations within the home during the in-home study (Fig. 4D). In the laboratory study, Combat bait stations had an average percent mortality of 81% at 14 d (Fig. 3B) across all home-collected populations. Despite the same AI and concentration as one of the professional products (0.05% fipronil), these differences could be explained by a number of reasons. Differences in formulation between the dried bait in Combat bait stations and other tested products may have impacted efficacy, as may the addition of the bait station itself. Though we did not observe this in our study, it is possible an accumulation of dead cockroaches inside bait stations could make baits inside less palatable, and future work should assess the impacts of bait containers on efficacy. Our results with Combat bait stations also differ from those found by Dingha et al. (2016), which found high reductions in cockroach populations following the application of Combat Source Kill Max bait (0.03% fipronil) enclosed in bait stations. Our study lacked an education component, which was included in the study by Dingha et al. (2016). In their study, the IPM education portion, which included workshops on German cockroach biology, cockroach control, and impacts of sanitation and sealing harborage sites, preceded bait application by 3 mo and reduced cockroaches trapped per day in many of their

study homes even before the introduction of baits. We also recognize that population differences, particularly in terms of resistance, between their study location (North Carolina) and ours (Kentucky) may have contributed to this difference. While our study provides unique insights into evaluating the same home-collected populations in both the home and the laboratory, the restricted geographic distribution of the *B. germanica* populations we evaluated is a limitation of the present study. Similar evaluations of product efficacy against populations across geographically distant regions, which may have been under differential selection pressure from pesticide use, would be valuable.

Also of interest is that, despite success in laboratory evaluations, the in-home performance of Combat gel bait was comparatively poor. Homes treated with Combat gel bait did not have significant reductions in cockroaches trapped compared to Month 0/Baseline until Month 2 (Fig. 4D). This suggests that this product was somewhat effective at reducing cockroach populations over time, but that efficacy took longer than with the professional products or with the Hot Shot bait stations. These findings align with DeVries et al. (2019a), which found 75% reduction in baseline trap catch with Combat and a 93% reduction with Maxforce FC in 1 mo. While their findings demonstrate a greater reduction in cockroach population at 1 mo following application of Combat gel bait than we observed (~30%), they do support a similar reduced in-home efficacy of Combat gel bait as compared to professional gel baits. DeVries et al. (2019a) also used a shorter trapping interval (24 h vs. 1 wk), which may have contributed to the greater reduction in the cockroach population seen in their study. It is important to recognize that, though a product could achieve high mortality/cockroach population reduction given enough time, if the time needed to cause substantial mortality is too long, that product may be impractical for dealing with cockroaches in homes. Those who are affected by cockroach infestations and are seeking ways of dealing with the infestation are unlikely to wait months for a product to take effect.

In addition to differences in formulation across products evaluated in this study, differences in active ingredients may have driven differences in product performance. While our study focused on population differences (based on trap catch) within treatment, rather than directly comparing treatments to one another, it is critical to acknowledge potential differences between actives/modes of action, as well as differences in active ingredient concentration between products. The Combat gel bait and the Maxforce FC Magnum gel bait are comparable formulations and both contain the same AI (fipronil), but at different concentrations—0.01% and 0.05%, respectively.

There are several factors that can influence cockroach population size within a home and that may have impacted treatment efficacy (reduction in cockroach trap catches) during the course of our study. Sanitation has been well documented as influencing cockroach populations within the home, as well as the efficacy of treatments aimed at population reduction (Schal 1988, Shahraki et al. 2010, Shahraki 2013, Noureldin and Farrag 2016, DeVries et al. 2019a, Wang et al. 2019b), with food, water, and harborage present within the home competing with baits and/or reducing cockroach interactions with baits. Additionally, despite their domiciliary nature, German cockroach populations can display seasonal variation, with populations tending to peak in warmer summer months (Koehler et al. 1987). Given the dynamic nature of the indoor home environment, we acknowledge that our study is limited. Our sample size for each treatment may not fully account for all external variables impacting cockroaches in the home, and thus we can only speak to the individual treatments we evaluated and their ability to reduce populations as compared to efficacy in the laboratory. Future work should expand upon this to be able to draw stronger conclusions about bait performance in the home.

All products evaluated in this study are registered and labeled for use to control cockroaches. However, when tested against home-collected populations, even under controlled laboratory conditions, several of these products start to falter. In our laboratory assays, at 28 d, Combat gel baits caused significantly lower average mortality than all other products evaluated in this study (Fig. 3C). This lack of efficacy is only magnified when these bait products are brought into the home, where additional variables such as food competition, in addition to resistant populations, present challenges to product efficacy. It is in the home that we also see products that performed promisingly in the laboratory (Combat gel bait) fail to reduce cockroach populations in a timely manner. Currently, laboratory assays for bait product registration, which are governed by the United States Environmental Protection Agency (EPA), are not required to incorporate resistant cockroach populations (EPA 2022). Simply, for "cockroaches" to be included a product label, only a single population each of German cockroaches and American cockroaches (*Periplaneta americana* (L.)) is required to be used in testing. As seen in the in-home component of our study, this can be problematic when these products are used for the management of cockroach infestations in homes, where the development of insecticide resistance has been widely documented. We believe that, for effective products to be available to consumers, it is critical for there to be a shift in testing requirements, starting with requiring the use of home-collected, insecticide-resistant populations in product testing and reporting on resistance ratios for each population and product evaluated. Furthermore, continued challenges of behavioral resistance through mechanisms such as glucose aversion (Wada-Katsumata and Schal 2024), should also be addressed in product efficacy evaluation.

Material costs associated with professional gel bait applications were 1.3× higher (applied cost)/3.6× higher (realized cost) than any of the consumer products evaluated in our study, not taking into account labor costs associated with time of application. Given these high costs, consumer products remain a widely utilized option. Proper product selection is key for management success, and thus it is critical for consumer bait products to be empirically evaluated. There are many bait products as well, that are marketed to consumers for use within their homes and that are available at hardware, supercenter, grocery, and convenience stores. As residents discern what products might be most effective, they may come across university resources, which heavily promote the use of baits due to their relatively low risk of pesticide exposure (Potter 2018, Layton and Goddard 2019, Ogg and Ogg 2019, Sutherland et al. 2019, Koehler et al. 2022). However, most of these materials do not distinguish between consumer and professional baits, the latter of which are not marketed for consumer use and are not readily available at local retailers. That said, products marketed for the professional pest management industry are available through online retailers, which will likely impact structural pest management in the future.

This study demonstrates that while some consumer-grade products may show high mortality in laboratory studies, some struggle to effectively control cockroaches under conditions within the home, which differentiates them from professional products in terms of performance. Without distinctions made within recommendations for bait use featured in such extension materials, it is likely that residents looking to treat cockroaches

in their homes will not make the distinction between professional and consumer-grade products either. This, in turn, can lead to experiences in which bait products were ineffective for cockroach control, driving the perception that cockroaches cannot be controlled. Despite their limitations, consumer-grade baits remain the most effective DIY control method for German cockroaches. Therefore, general recommendations for bait use by academic and extension personnel should continue to be made. However, as we continue to recommend baits, we should also work toward developing truly effective solutions that can be provided to residents struggling with cockroaches.

The findings of our study, as well as a previous study examining consumer-grade aerosol and liquid ready-to-use products (Gordon et al. 2024), suggest there are few options available to residents that can successfully control cockroaches within their homes. Of the consumer-grade bait products we evaluated, Hot Shot liquid bait stations performed well in both laboratory and in-home evaluations and appear promising candidates in housing settings where professional pest control may not be affordable or available, though further study is needed. Moreover, these liquid baits should also be evaluated as a possible professional tool given their short application time and cost compared to alternative baiting products and practices. Ineffective pest control not only allows cockroaches to persist within the home, but it furthers resident exposure to cockroach allergens and increases the risk of associated negative health impacts. Products marketed for cockroach control, whether aerosol/spray formulations or bait products, should undergo sufficient testing to ensure they are equipped to perform under the variable conditions of the indoor home environment. Despite well-known and effective tools for cockroach control, for many residents struggling with cockroach infestations, these tools are not accessible and the tools that are accessible are ineffective. Products that are labeled for cockroaches should be able to effectively control cockroaches, and anyone seeking to control cockroaches in their home should be able to do so.

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Supplementary data

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

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Data Availability

Data are available in the supplementary materials.

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