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Effects of over-the-counter aerosol products on sociotomy of *Monomorium pharaonis* (Hymenoptera: Formicidae)

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The Pharaoh ant, *Monomorium pharaonis* (L.), is a widely distributed invasive tramp ant species. Due to their ability to frequently relocate nest sites when disturbed, Pharaoh ants are particularly challenging to manage. This study examined the colony movement patterns of different colony sizes of the Pharaoh ant in response to chemical disturbances caused by varying over-the-counter aerosol insecticide application rates. Three aerosol products, 3 application rates, and 4 colony sizes were tested. Essential oil-based insecticides exhibited a higher probability of inducing budding at all colony sizes when applied at a high rate. In contrast, pyrethroid-based insecticides increased the probability of inducing budding at a low application rate. The number of workers present outside the main nest in the essential oil-based insecticide-treated group decreased with increasing application rate, whereas the number of workers present outside the main nest increased in pyrethroid-based insecticide-treated groups. Furthermore, the density of workers outside the main nest appeared to play a role in influencing the final nest site after budding. The number of worker ant carcasses observed on pyrethroid-treated surfaces was significantly greater than on surfaces treated with the essential oil-based insecticide and controls. The effects of aerosol product type, colony size, and insecticide application rate on Pharaoh ant colony movement are discussed.

Keywords: pyrethroid, natural product insecticide, budding, ant control

Introduction

The Pharaoh ant, *Monomorium pharaonis* (L.), is an important indoor pest ant species known to infest residential and commercial structures. It exhibits tramp ant characteristics such as true polygyny, small and sterile workers, short queen lifespan, and colony reproduction through budding (Edwards and Baker 1981, Passera 1994, Alharbi et al. 2019). Due to its synanthropic nature, the Pharaoh ant can be easily dispersed to new environments to establish a colony, and when disturbed, it splits or relocates the nest location (Hölldobler and Wilson 1990, Lutinski et al. 2015).

Sociotomy, or budding, in ants refers to the process by which a reproductively competent group—typically comprising workers, reproductives, and broods—separates from the parent colony and migrates to a new location to establish a new colony (Vail and Williams 1994). This behavior has been frequently documented in many tramp ant species, such as *Solenopsis invicta* Buren, *Linepithema humile* (Mayr), *Paratrechina longicornis* (Latreille), and *M. pharaonis* (Linnaeus) (Vargo and Porter 1989, Passera 1994, Heinze and Tsuji 1995, Suarez et al. 2001, Buczkowski and Bennett 2009a, Kamarudin et al. 2011). Sociotomy is vital for colony survival, especially when colonies are physically or chemically disturbed (Buczkowski et al. 2005, Buczkowski and Bennett 2009a).

Budding in Pharaoh ants is often triggered by factors such as interspecific competition, aggression, insufficient resources, and physical or chemical disturbances (Buczkowski et al. 2005; Buczkowski and Bennett 2009a; Tay and Lee 2015). They frequently nest in inaccessible areas, such as beneath wall panels, in attics, inside wall voids, and behind electrical outlets (Harris 1991; Fowler et al. 1993; Vail 1996; Klotz et al. 2008), making Pharaoh ants particularly challenging to control. Control strategies, such as barrier treatments with high-repellency insecticides, can create unwanted disturbances that trigger budding, thereby exacerbating the infestation (Buczkowski et al. 2005).

Homeowners and tenants often try to manage pest control on their own by using over-the-counter (OTC) aerosol products instead of hiring professional pest control services (Lee 2002, Carlton et al. 2004, Wang and Bennett 2010). While professional services achieve better pest control outcomes, many consumers are deterred by the cost (Wang and Bennett 2010, DeVries et al. 2019). OTC aerosol products are popular due to their affordability, easy availability, and straightforward application (Bennett et al. 1983, DeVries et al. 2019). However, most OTC aerosol products available contain pyrethroids, which can induce budding in Pharaoh ants, potentially leading to spreading infestations (Buczkowski et al. 2005, Tay and Lee 2015).

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Understanding how abiotic and biotic factors influence budding behavior is essential for designing effective pest management strategies for the Pharaoh ant. Buczkowski et al. (2005) identified that active ingredients, such as cinnamaldehyde, cypermethrin, and bifenthrin, trigger colony budding. Subsequently, Buczkowski and Bennett (2009a) examined the effects of various physical disturbances on Pharaoh ant colony budding and the population dynamics of colony fragments. Tay and Lee (2015) investigated the causes of colony budding, evaluating factors such as physical and chemical disturbances, interspecific competition, and resource depletion. Edvison et al. (2012) reported that Pharaoh ants use pheromone trails produced by foragers to select their potential budding sites. However, these studies were conducted using standard subcolonies of Pharaoh ants of similar colony sizes. In the field, Pharaoh ant colonies can vary in size, ranging from as few as 5 workers and 50 pieces of brood to a colony of 10,000 workers (Klotz et al. 2008).

In this study, we examined how colony size and aerosol application rates impact the budding of the Pharaoh ant. We employed 3 widely used commercial aerosol products and monitored their effects on the colony over time.

Materials and Methods

Insects

The study was conducted using *M. pharaonis* obtained from the USDA-ARS, Center for Medical, Agricultural, & Veterinary Entomology in Gainesville, Florida, in 2020. The ants were reared under laboratory conditions of 27 ± 1 °C, 70 ± 2% RH, and a 12:12 L:D cycle in arenas coated with fluon at the University of California, Riverside, over a span of 4 yr. Water and a 10% sucrose solution were provided ad libitum, and Tetra Goldfish Flakes (Tetra GmbH, Melle, Germany), along with raw tuna obtained from Costco, served as protein sources and were provisioned weekly.

Experimental Design

The experimental arena comprised 6 fluon-coated polyethylene containers (8.7 cm in diameter, 7.8 cm in height), including 1 central container A, which was connected to 4 other containers C to F by 1-m lengths of Tygon tubing that served as potential budding sites. Container B linked to container A through a 5 cm length of Tygon tubing and contained treated filter paper (Fig. 1). All Tygon tubes were sealed with cotton until the end

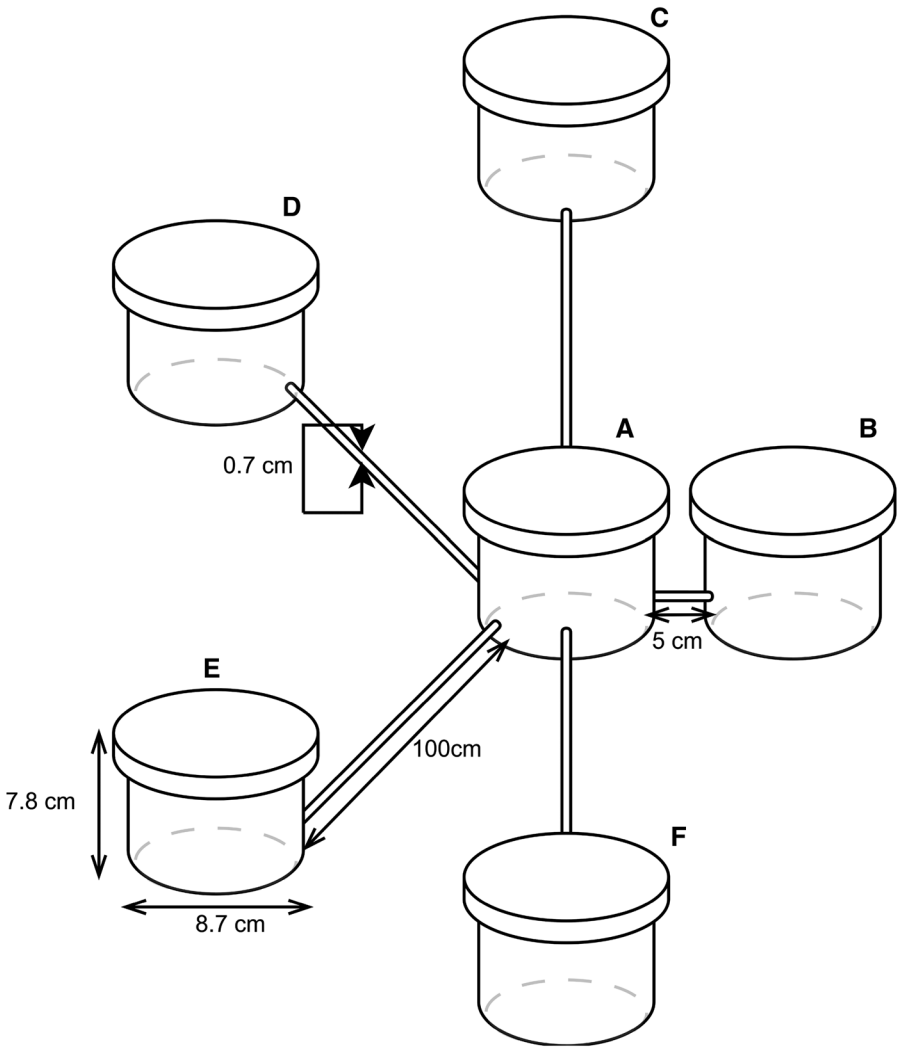

Fig. 1. The experimental setup used in this study. The polyethylene containers are labeled as A) Original nest site; B) Insecticide application site; C to F) Potential budding sites.

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of the acclimatization period to prevent the ants from budding immediately after being introduced to the setup that could happen due to physical disturbances.

All containers, except for container B, were provisioned with 0.03 g of canned tuna (Kirkland Signature, Issaquah, Washington) and boiled egg yolk on a weekly basis. Water and a 10% sucrose solution were provided ad libitum. Additionally, each container included a small piece of folded cardboard (5 × 5 cm) for shelter. All containers, except for container B, were designed identically. All Tygon tubes were thoroughly cleaned using DECON 90 (Decon Laboratories, Hove, UK) before the experiment to eliminate any potential chemical residues from the manufacturing process that could influence the results.

In the experimental setup, a subcolony of Pharaoh ants with the following composition was used: (i) 100 workers, 10 mg of mixed brood stage, and 1 queen; (ii) 200 workers, 25 mg of mixed brood stage, and 2 queens; (iii) 400 workers, 50 mg of mixed brood stage, and 3 queens; (iv) 800 workers, 100 mg of mixed brood stage, and 4 queens. The insects were placed in central container A to acclimate for 7 d.

Three common household aerosol products were examined: Zevo Crawling Insect Killer—Ants, Roaches, Spider (geraniol 1.3%, cinnamon oil 0.2%, The Procter & Gamble Company, Cincinnati, Ohio), Raid Ant & Roach Killer 26 (imiprothrin 0.06%, cypermethrin 0.1%, S.C. Johnson & Son, Racine, Wisconsin), and Black Flag Dry Ant and Roach Killer (imiprothrin 0.1%, gamma-cyhalothrin 0.025%, Spectrum Brands, Madison, Wisconsin). Each aerosol product was applied to a piece of filter paper (5 × 7.5 cm) for 1, 2, or 3 s. The insecticide dispense rates for the tested aerosol products were assessed by subtracting the product's weight after 1 s of application from its weight before application. This process was repeated 10 times for each aerosol product. The mean dispense rates ± SEM across all tested products were relatively consistent [(Zevo: 2.84 ± 0.08 g/s; the amount of active ingredients dispensed at 1, 2, and 3 s were 42.6 ± 1.2 mg, 83.2 ± 2.4 mg, and 127.8 ± 3.6 mg, respectively; Raid: 2.84 ± 0.05 g/s; the amount of active ingredients dispensed at 1, 2, and 3 s were 4.54 ± 0.1 mg, and 9.08 ± 0.2 mg, 13.62 ± 0.3 mg, respectively; Black Flag: 2.97 ± 0.02 g/s; the amount of active ingredients dispensed at 1, 2, and 3 s were 3.71 ± 0.03 mg, 7.42 ± 0.06 mg, and 11.13 ± 0.09 mg, respectively)]. For the control, water was applied to the filter papers. The treated filter paper was left in the fume hood to dry for 2 h before being placed in container B at the end of the acclimatization period. To examine the impact of aerosol treatments on ants' exploratory activity, the number of live workers present outside the main nest, nest sites (original nest site and potential budding sites) where a colony or colony fragments were observed, in all unoccupied containers (all containers with no colony/colony fragment present) was recorded once a week for 6 wk and calculated the weekly average. Workers found in the Tygon tubes were counted as part of the container to which each tube was connected. The degree of colony relocation or budding was evaluated based on when a potential budding site (containers C to F) is occupied by reproductively competent colony fragments. A reproductively competent colony fragment, produced via budding, is defined as a colony fragment consisting of approximately 50 or more workers, at least 1 queen, and/or the presence of broods (Peacock et al. 1955, Vail and Williams 1994, Buczkowski et al. 2005, Tay et al. 2014). Although Pharaoh ant workers are capable of rearing new reproductives from existing larvae (Vail and William 1994), we used the definition of a budded colony in other studies (Buczkowski et al. 2005, Tay et al. 2014) that included the presence of queen. In the event that the colony relocated and nested in the Tygon tube instead of containers C to F, we designated it based on which container the Tygon tube is connected to. To determine whether the toxicant reached container A and triggered budding, we assessed the repellency and lethality of treated surfaces based on the weekly average number of live Pharaoh ant workers in container B over a 6-wk period and the number of worker carcasses observed in container B at the end of the study, respectively. We chose to record the number of worker carcasses in container B because fewer worker carcasses would indicate that workers could return to container A and deliver toxicants or insecticide residues, or that they were repelled and never contacted the treated surface. Conversely, more worker carcasses would suggest the opposite. A higher live worker presence in container B would indicate low repellency, whereas a lower presence would indicate strong repellency. Worker carcasses remained in container B until the total count was recorded at the end of the study. Studies have shown that the number of live workers present in specific locations might relate to where colonization occurs (Fowler et al. 1993, Edvison et al. 2012). To determine whether the number of live workers present at each of the 4 potential budding sites would influence the final budding location, the highest number of live workers recorded at each potential budding site before colony fragmentation or relocation was compared to the final budding location. Data were collected in the morning on days 1, 3, 5, and 7 and then weekly for 5 more wk. Three replicates were conducted for each treatment.

Statistical Analysis

To examine the effect of colony sizes, aerosol products, and insecticide application rates on the response of each replicate colony, we performed a discrete-time survival analysis to evaluate the probability of budding occurring during the 6-wk period (Suresh and Severn 2022). We first modeled the hazard probability that is defined as the probability of budding at a specific week given that budding has not occurred before that week, with a logit link based on when the first observation on colony fragmentation or relocation in each treated and untreated group was recorded to estimate how different factors affect the timing of budding occurring. The hazard probability at week t is expressed as: $h(t) = 1 - (1/(1 + \exp(-\eta)))$, where η is the linear predictor from the model and is obtained as the sum of coefficients of all variables (Suresh and Severn 2022). After estimating the hazard probability at each time point, we converted the hazard probability to survival probability $S(t)$ to determine the cumulative probability of budding not occurring using $S(t) = S(t - 1) \times (1 - h(t))$ (Suresh and Severn 2022). Finally, to calculate the cumulative probability of budding occurring, we converted $S(t)$ to $C(t)$ using $C(t) = 1 - S(t)$. Discrete-time survival analysis was conducted using the Survival package (Therneau 2024), and a graph of budding probability was generated using ggplot2 in R (Wickham 2016).

To determine the effect of the number of live workers at each potential budding site before budding on the location of the final nest site after budding, we calculated the percentage of present live workers as the highest number of workers observed during the experiment before colony fragmentation or relocation occurred at each potential budding site, divided by the initial number of workers in the corresponding colony size (100, 200, 400, or 800 workers), and analyzed this using binary logistic

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regression, a statistical approach to model the relationship between one or more independent variables and a binary outcome (in the case of this study, whether or not a site becomes the final nest site), with 2 additional covariates: colony size and insecticide application rate. The binary logistic regression was carried out using IBM SPSS Version 29.0. The weekly average percentage of workers present outside the main nest across 6 wk (the percentage of workers present outside the nest at each time point was calculated as the total number of workers in all unoccupied containers divided by the initial number of workers in the corresponding colony size; the weekly average percentage was then determined by averaging these percentages across all time points), the weekly average percentage of live workers present in container B during the experiment (the percentage of workers present in container B at each time point was calculated as the number of live workers in container B divided by the initial number of workers in the corresponding colony size; the weekly average percentage was then found by averaging these percentages across all time points), and the percentage of cumulative ant carcasses in container B (the number of worker carcasses in container B at the end of the experiment divided by the initial number of workers in the corresponding colony size) were transformed into arcsine square roots and each subjected to one-way ANOVA. Mean values were compared using the Least Significant Difference (LSD) test, and one-way ANOVA was carried out using IBM SPSS Version 29.0.

Results

Colony Relocation

Colony size did not significantly affect the discrete-time survival model across 3 insecticide application rates and aerosol products ($P > 0.05$), indicating the colony sizes used in this study did not influence Pharaoh ants' response to chemical disturbances. At the 1-s treatment, all aerosol products exhibited a higher probability of budding from week 1 to week 6 (Fig. 2A), with Black Flag and Raid showing significantly higher probabilities of budding ($Z = 3.48$, $P < 0.001$; $Z = 2.10$, $P < 0.05$). This indicates that Black Flag and Raid are more likely to induce and facilitate budding than the Zevo-treated group and controls. At the 2-s treatment, all aerosol products showed a higher probability of budding over the same period (Fig. 2B). Compared to Zevo's performance in the 1-s treatment, its probability of budding increased and became significantly higher than the controls ($Z = 2.39$, $P < 0.05$). Additionally, the budding probability of colonies treated with Zevo overlapped with that of Black Flag (Fig. 2B), which was also significantly higher than the controls ($Z = 2.42$, $P < 0.05$). At the 3-s treatment, the budding probabilities of colonies treated with Zevo- and Raid-treated groups was significantly higher than the budding probability of controls ($Z = 2.85$, $P < 0.05$; $Z = 2.26$, $P < 0.05$). In contrast, the budding probability of Black Flag-treated groups significantly decreased ($Z = -3.613$, $P < 0.001$) and became statistically insignificantly different from that of the controls (Fig. 2C), indicating Black Flag had no significant effect on colony relocation at the 3-s treatment.

Presence of Workers Outside the Main Nest

At the 1-s treatment, no aerosol product caused a significant difference in the percentage of workers present outside the main nest compared to the controls in colony sizes A and C (Fig. 4). The Zevo-treated group exhibited significantly fewer workers outside the nest in colony size B, while the Raid- and Black Flag-treated groups showed significantly fewer workers in both

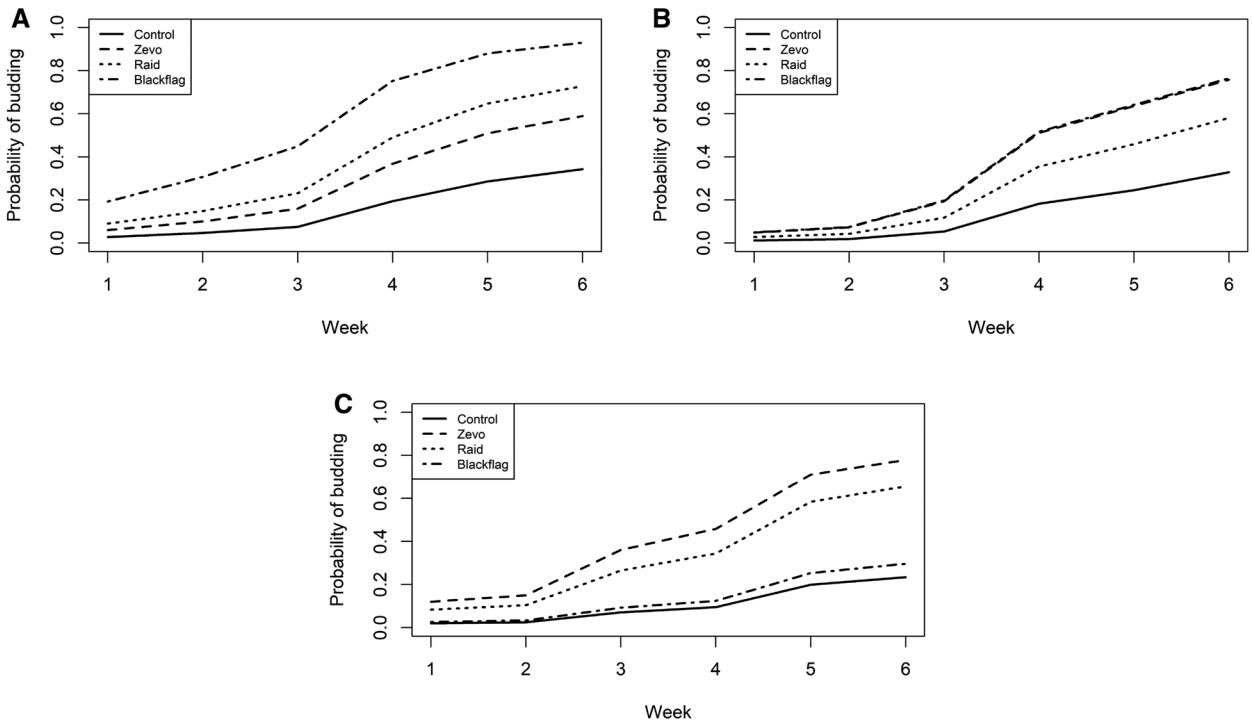

Fig. 2. Probability of budding by aerosol products over 6 wk after receiving treatment with different insecticide application rates. A) Probability of budding by aerosol products over 6 wk at 1-s treatment. B) Probability of budding by aerosol products over 6 wk at 2-s treatment. C) Probability of budding by aerosol products over 6 wk at 3-s treatment.

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colony sizes B and D (Fig. 4). At the 2-s treatment, Zevo resulted in significantly more workers being present outside the nest compared to the controls in colony size A and significantly fewer in colony size D. Raid also showed significantly fewer workers outside the nest in colony size D, whereas Black Flag had no significant effect on worker presence outside the nest in any colony size (Fig. 4). At the 3-s treatment, no aerosol product caused a significant difference in the percentage of workers present outside the nest compared to the controls in colony sizes A and B (Fig. 4). However, Raid and Black Flag resulted in significantly fewer workers outside the nest in colony size C (Fig. 4). Additionally, the Zevo-treated group showed a significant decrease in worker presence compared to the 1-s treatment in colony size D, ultimately leading to significantly fewer workers being present outside the nest than the controls (Fig. 4).

In container B, all tested aerosol products significantly reduced the percentage of Pharaoh ant workers on treated surfaces across all colony sizes and insecticide application rates compared to the controls (Fig. 5).

Number of Worker Carcasses Observed on Treated Surfaces

Across all tested aerosol products and insecticide application rates in colony size A, the number of worker carcasses in container B was not significantly different from that in the controls (Fig. 6). In the Raid-treated groups, the number of worker carcasses in container B was significantly higher than in the controls for colony sizes B and D at 1-s treatment and colony sizes B, C, and D at 2- and 3-s treatments (Fig. 6). The Black Flag-treated groups initially showed no significant difference in the number of worker carcasses across all colony sizes at the 1-s treatment (Fig. 6). However, at the 2- and 3-s treatments, significantly more worker carcasses were observed in colony sizes C and D, and in colony sizes B, C, and D, respectively. In contrast, the Zevo-treated groups showed no significant differences in the number of worker carcasses across all insecticide application rates and colony sizes compared to the control (Fig. 6).

Budding Activity

Colony size was not a significant predictor in the logistic regression model for any of the tested aerosol products, indicating that different colony sizes used in this study did not influence budding activity (Table 1). Insecticide application rate was a significant predictor only in Black Flag-treated groups. The number of workers present at each potential budding site significantly influenced the logistic regression model in the controls and Raid-treated groups ($B = 0.328$, df = 1, $P < 0.001$; $B = 0.291$, df = 1, $P < 0.001$), suggesting that locations with more workers were more likely to become the final budding sites in those groups. Although potential budding sites with a higher number of workers also had an increased likelihood of becoming the final nest location in Black Flag-treated groups, this effect was not statistically significant ($B = 0.132$, df = 1, $P = 0.067$).

Table 1. Binary logistic regression for the influence of colony size, percentage of visiting workers, and application rate on colony relocation in response to different aerosol products

Aerosol	Variable	*B*	S.E.	df	*P* value
Control	Colony size			3	0.604
	Percentage of visiting workers	0.328	0.089	1	<0.001*
	Application rate			2	0.481
Zevo	Colony size			3	0.468
	Percentage of visiting workers	0.027	0.063	1	0.675
	Application rate			2	0.37
Raid	Colony size			3	0.19
	Percentage of visiting workers	0.291	0.08	1	<0.001*
	Application rate			2	0.101
Black Flag	Colony size			3	0.108
	Percentage of visiting workers	0.132	0.072	1	0.067
	Application rate			2	0.044*

B, B value; df, degree of freedom; S.E., standard error.
*$P < 0.05$.

Discussion

Our results showed that colonies typically took 1 to 3 wk to respond to the treatment (Fig. 3). In contrast, Tay and Lee (2015) demonstrated that directly applying deltamethrin to Pharaoh ant workers and introducing them into the colony led to immediate nest relocation within a day. This difference in response time indicates that the chemical disturbance was not immediately delivered to the colony in this study. It could also be attributed to differences in the experimental setup: in the present study, ants were given the choice of whether to contact with the treated surface, whereas in Tay and Lee (2015), colonies were forced to contact with the chemical. Our results showed that all tested aerosol products significantly reduced the exploratory activity of Pharaoh ant workers on treated surfaces (Fig. 5). However, more ant carcasses were observed in container B in the Raid- and Black Flag-treated groups compared to the Zevo-treated groups and the controls, although the differences were not always significant (Fig. 6), suggesting that Zevo exhibited strong repellency, while Raid and Black Flag demonstrated strong contact toxicity. This finding aligns with previous research indicating that pyrethroids act as contact irritants rather than spatial repellents, like essential oil components do (Yoon et al. 2009, Huang et al. 2020, Gaire et al. 2024). At the conclusion of the study, the strong and persistent scent of formulation was still noticeable in the Zevo-treated groups, but not in the Raid- or Black Flag-treated groups. This further suggested that chemical disturbance in the Zevo-treated group was delivered spatially, whereas in the Raid- and Black Flag-treated groups, it was likely mediated by the ants. Additionally, it was observed that Pharaoh ant colonies may relocate again after budding to a new site (Fig. 3). This occurred because the queens occasionally moved to other locations after budding. Since colony fragments require the presence of a queen to be considered reproductively competent, the presence of colony fragments fluctuated.

Colony size was excluded in discrete time survival analysis due to its insignificant influence on probability of colony budding in all treatments (Fig. 2). The lack of influence of colony size may be due to the relatively narrow size range of the colonies compared to other studies (Buczkowski et al. 2005, Buczkowski and Bennett 2009b, Vail and Williams 1994). Larger colonies with more queens may be more conducive to

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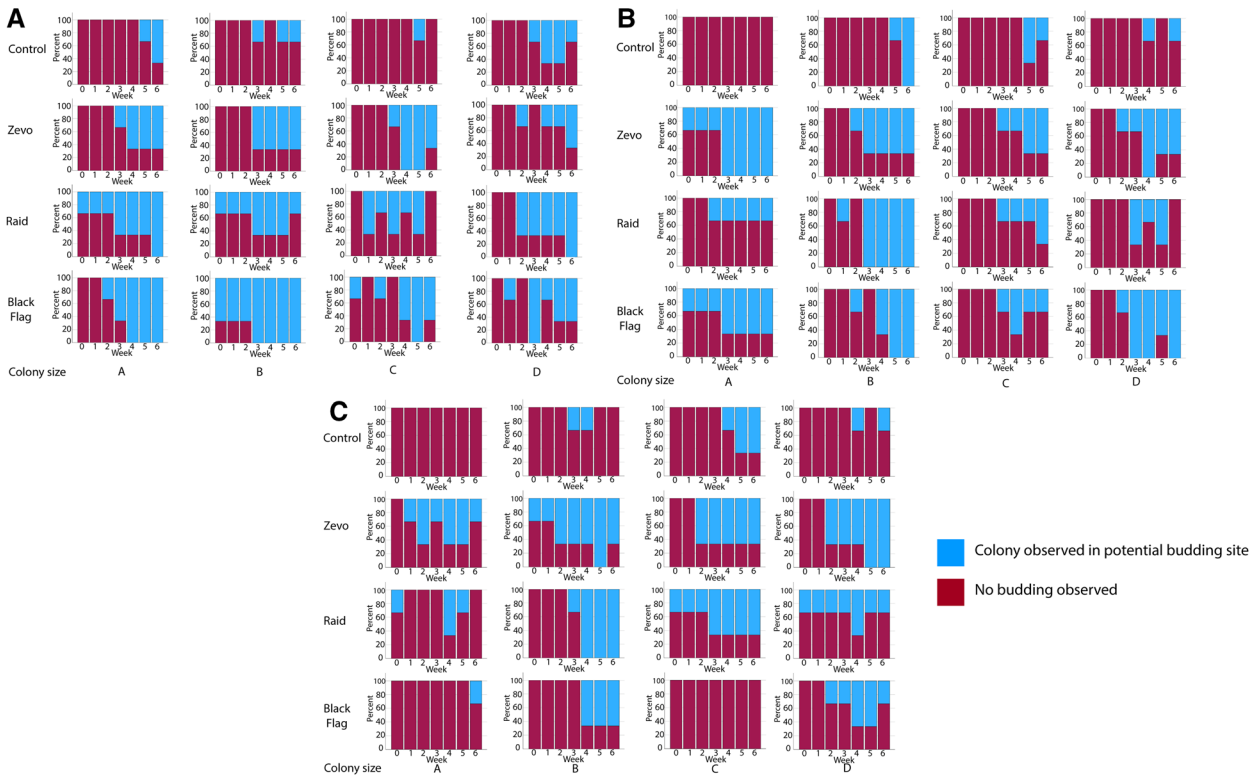

Fig. 3. Pharaoh ant colony movement over 6 wk after receiving treatment with different insecticide application rates. A) Colony movement by aerosol products over 6 wk at 1-s treatment. B) Colony movement by aerosol products over 6 wk at 2-s treatment. C) Colony movement by aerosol products over 6 wk at 3-s treatment.

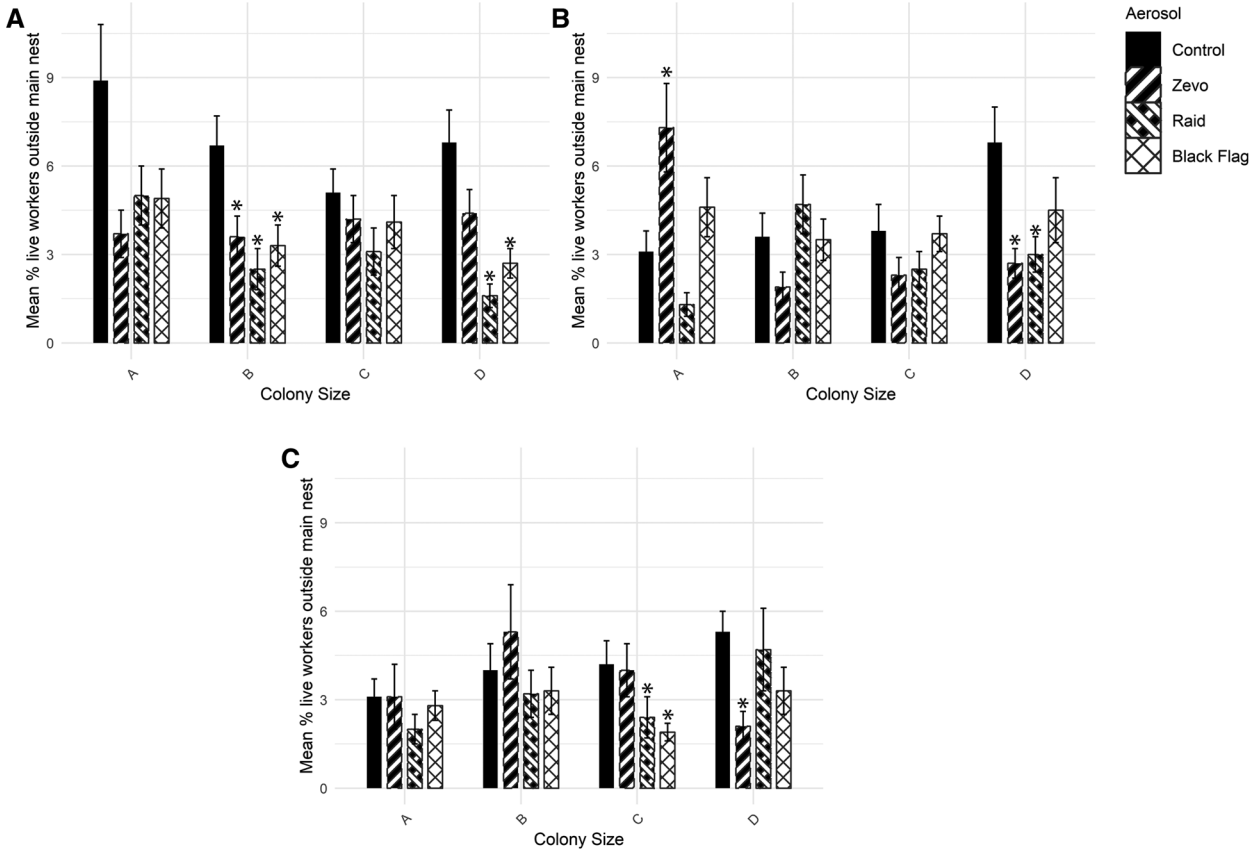

Fig. 4. Weekly mean percentage of workers outside the main nest observed in all nest sites in response to different aerosol products. A) Weekly mean percentage of workers outside the main nest over 6 wk at 1-s treatment. B) Weekly mean percentage of workers outside the main nest over 6 wk at 2-s treatment. C) Weekly mean percentage of workers outside the main nest over 6 wk at 3-s treatment. Means with * indicate significant difference within each colony size ($P < 0.05$; LSD).

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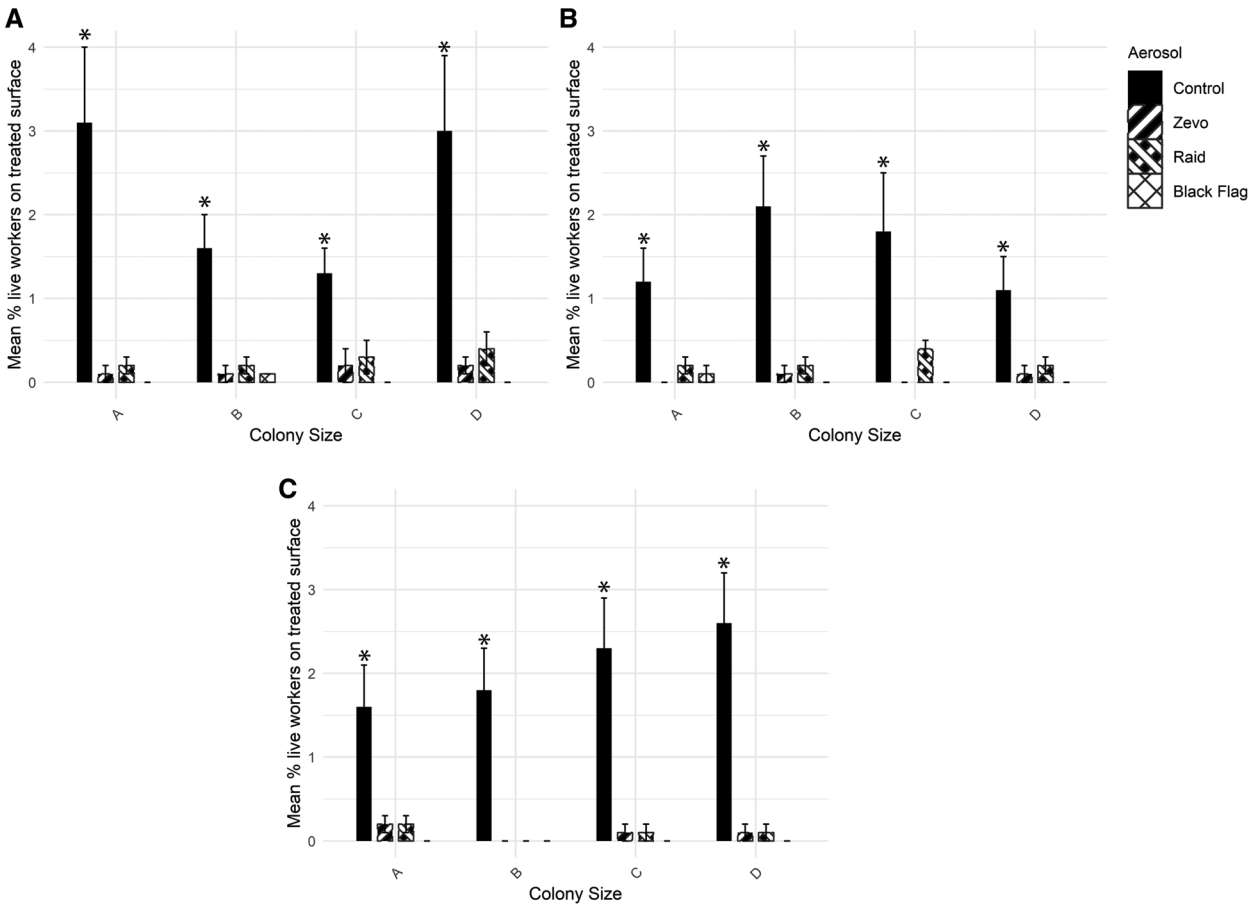

Fig. 5. Weekly mean percentage of live workers observed in container B in response to different aerosol products. A) Weekly mean percentage of live workers observed in container B over 6 wk at 1-s treatment. B) Weekly mean percentage of live workers observed in container B over 6 wk at 2-s treatment. C) Weekly mean percentage of live workers observed in container B over 6 wk at 3-s treatment. Means with * indicate significant difference within each colony size ($P < 0.05$; LSD).

budding and may suggest the significance of colony size in discrete time survival analysis. An increase in the probability of budding was also observed in the control groups over time, despite the absence of chemical exposure (Fig. 2). This is likely attributable to physical disturbance caused by weekly colony maintenance. However, because the maintenance procedure was standardized across both treated and untreated groups, all colonies experienced the same level of disturbance.

While the changes in the percentage of workers present outside the nest in colony sizes A, B, and C were inconsistent across all insecticide application rates following treatment with different aerosol products, a significantly lower presence of workers was predominantly observed in colony size D. Vail (1996) reported that as colony size increased, the percentage of workers outside the nest also increased. However, previous studies have also demonstrated that colony sizes do not impact the percentage of Pharaoh ants present outside the nest under control conditions (Lee and Lee 2002, Buczkowski and Bennett 2005). A similar phenomenon was likewise seen in *Tapinoma sessile* Say, where colony size does not significantly influence foraging activity (Buczkowski and Bennett 2009b). This discrepancy suggests that the tested aerosol products primarily affect exploratory behavior in large Pharaoh ant colonies. Since at least 600 Pharaoh ant workers are needed to establish a functional, attractive pheromone trail (Sumpter and Beekman 2003), the presence of workers outside the main nest was less responsive to treatments in colony sizes A, B, and C due to their smaller size.

The presence of more workers significantly influenced the location of final nest sites after budding in Pharaoh ants, as these ants use pheromone trails to relocate to potential nest sites (Evison et al. 2012). Fowler et al. (1993) also observed clustering of colonization attempts at specific locations, suggesting that colonization may be predictable. In this study, we found that Pharaoh ants tended to bud into potential nesting sites that had previously been visited by more workers under control conditions (Table 1). The same phenomenon was observed after Pharaoh ant colonies were treated with Raid (Table 1). In Black Flag-treated groups, the insecticide application rate was highly correlated with colony relocation (Fig. 2), which poses a key problem in the binary logistic regression model when explanatory variables are highly correlated, creating multicollinearity (Senaviratna and Cooray 2019). As a result, the insecticide application rate became a significant predictor, while the percentage of workers present did not. In contrast, neither predictor significantly influenced the location of the final budding site in Zevo-treated groups, most likely because Zevo induced budding more rapidly than Raid and Black Flag.

The colony relocation for each tested aerosol product exhibited distinct trends in response to increasing application rates

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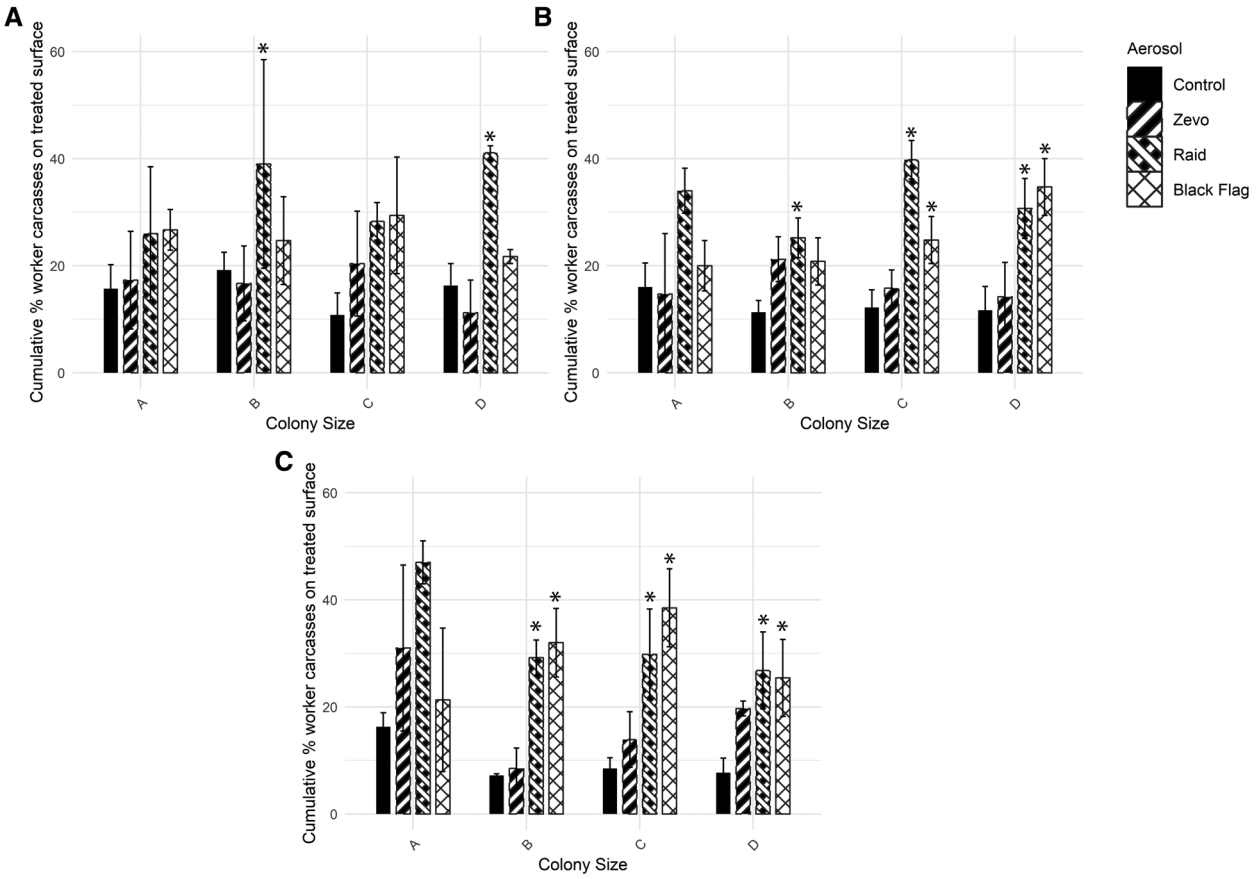

Fig. 6. Mean percentage of cumulative worker carcasses observed in container B in response to different aerosol products. A) Mean percentage of cumulative worker carcasses observed in container B at week 6 at 1-s treatment. B) Mean percentage of cumulative worker carcasses observed in container B at week 6 at 2-s treatment. C) Mean percentage of cumulative worker carcasses observed in container B at week 6 at 3-s treatment. Means with * indicate significant difference within each colony size ($P < 0.05$; LSD).

(Fig. 3). Previous studies have reported that essential oils show increasing repellency with higher insecticide application rates (Xu 2012), and a similar phenomenon has also been observed with pyrethroids (Wen et al. 2022). However, in the Zevo-treated group, Pharaoh ant colonies displayed increased movement at higher application rates (Fig. 3). In contrast, the Raid- and Black Flag-treated groups, particularly the latter, showed decreased movement across all colony sizes (Fig. 3). Other studies have indicated delayed budding behavior following pyrethroid treatment (Buczkowski et al. 2005, Knight and Rust 1990). This phenomenon could be attributed to differences in the properties of the active ingredients. Essential oil components act as true spatial repellents, whereas pyrethroids function as contact irritants (Yoon et al. 2009, Huang et al. 2020, Gaire et al. 2024). In the Zevo-treated group, the number of worker carcasses on treated surfaces was not significantly different from the controls (Fig. 6), and significantly fewer live ants were observed in container B (Fig. 5), indicating that Zevo-treated surfaces had low toxicity or strong repellency. In contrast, the Raid- and Black Flag-treated groups showed significantly more worker carcasses on treated surfaces (Fig. 6), suggesting that workers were not repelled but contacted the treated surface, became irritated, and were ultimately knocked down and killed, resulting in fewer contaminated workers returning to the nest, thereby delaying nest relocation. However, it is noteworthy that observations on workers' activity and colony relocation were made at nine discrete time points, which may not provide a representation of the actual numbers of workers that visited each nest site during the 6-wk period, and colony relocations may occur when observations were not being made.

This study investigated the movement patterns of Pharaoh ant colonies of various sizes under different insecticide application rates using OTC aerosol products. Aerosol products provide several advantages, including ease of acquisition, simplicity of use, affordability, and immediate lethality, making them the most commonly used formulation in household settings (Bennett et al. 1983, Lee 2002). However, effective control of Pharaoh ants necessitates the elimination of the entire colony, yet these ants often nest in inaccessible locations. Most residual insecticide sprays are inefficient for managing Pharaoh ant infestations because they only kill a small portion of foragers. Additionally, if Pharaoh ants sense chemical disturbances, the colony may fragment and migrate, further spreading the infestation (Oi et al. 2000, Buczkowski et al. 2005, Tay and Lee 2015). Current control methods for Pharaoh ants focus on baiting with active ingredients that have delayed toxicity, allowing toxicants to be thoroughly distributed throughout the colony via trophallaxis with minimal disturbances (Oi et al. 2000).

In addition to selecting appropriate control strategies, effective management of Pharaoh ant infestations also relies

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on inspection and monitoring to detect the presence of the pest and assess the effectiveness of these strategies. Pest ant monitoring is often performed by counting the number of ants found on index cards with food at various locations within an infested structure (Oi et al. 1994, Oi et al. 1996). Given that locations with more worker ants visiting are more likely to become final budding sites, this information can be valuable for optimizing bait placement in Pharaoh ant control, as colonies situated closer to toxic bait are more likely to be impacted (Oi et al. 2000). In contrast, aerosol sprays primarily affect exposed foragers and do not reach hidden nest sites, highlighting the limitations of OTC aerosol sprays and the importance of using baits in the management of Pharaoh ants.

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Conflict of interest

The authors declare no conflict of interest.

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