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Feature Article

Advancing Invasive Ant Management: Innovative and Targeted Strategies

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Abstract

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Invasive ant management has evolved from relying solely on broad-spectrum toxic baits to incorporating more targeted, environmentally friendly strategies. This shift toward precision and sustainability inspires future management to focus on integrated, species-specific, and cost-effective approaches. This review highlights innovative approaches, including hydrogel bait formulations, foraging disruption/enhancement via species-specific trail pheromones, insecticide-coated prey baits, and microbial control agents to enhance effectiveness. We also highlighted several advanced techniques involving RNA interference and AI-powered tools that can be integrated into the current invasive ant management framework. Throughout the review, we outline the advantages and limitations of each method under various field scenarios, offering insights into how these innovations can be effectively integrated into invasive ant management. We also emphasize the strategy of utilizing different methods to respond to varying population density levels to maximize control efficacy while minimizing non-target impacts. Tailoring management tactics to population dynamics allows for aggressive suppression during peak infestations and the use of species-specific tools to support ecosystem recovery as populations decline.

Key words: Invasive ant, Baiting, Hydrogel, Biorational control, Artificial intelligence.

INTRODUCTION

Human activities have increasingly facilitated the global spread of invasive species, resulting in significant economic and ecological consequences worldwide (Bertelsmeier *et al.* 2017; Sardain *et al.* 2019). In 2019, the annual global cost of biological invasions was estimated to exceed US$423 billion (Diagne *et al.* 2021; Roy *et al.* 2023). Among invasive alien species, ants are one of the most damaging taxa, with an estimated annual economic impact of US$119 million (Angulo *et al.* 2022). While invasive ants are typically not problematic in their native ecosystems, they can become highly disruptive pests in introduced regions, causing ecological and economic harm (Holway *et al.* 2002). Well-known invasive ant species including the red imported fire ant (*Solenopsis invicta*), Argentine ant (*Linepithema humile*), little fire ant (*Wasmannia auropunctata*), tawny crazy ant (*Nylanderia fulva*), yellow crazy ant (*Anoplolepis gracilipes*), Asian needle ant (*Brachyponera chinensis*), and African big-headed ant (*Pheidole megacephala*). The development of invasive ant management tools has progressed alongside advancements in technology, with

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a growing emphasis on improving species specificity, enhancing efficacy, and ensuring cost-effectiveness. In this review, we examine the history and evolution of invasive ant management, with a particular focus on the rise of conventional baiting strategies. We then explore emerging control approaches including several biorational control innovation (defined as the use of specific and selective chemical, biological and physical agents for controlling pests which results in minimum no-target impacts; Haddi *et al.* 2020) and conclude with insights into future directions for invasive ant management.

EVOLUTION OF INVASIVE ANT CONTROL: TRANSITIONING FROM CONTACT INSECTICIDE TO BAIT

Residual insecticide treatments were initially employed to manage invasive ants with different formulations adapting to different scenarios (Klotz *et al.* 1995). Treatments incorporating repellent insecticide at perimeter inside or around human structures can knockdown foraging workers, disrupt the establishment of foraging trails, and prevent ants from entering (Knight & Rust 1990; Klotz *et al.* 2007). Instead of the rapid contact toxic effect, non-repellent insecticides can be transferred within colonies through worker contacts (e.g., grooming and necrophoresis) (Soeprono & Rust 2004; Choe & Rust 2008; Wiltz *et al.* 2010). While residual insecticide treatments result in rapid and significant reduction in foraging workers, they rarely achieve colony eradication, as reproductives (e.g., queens and winged alates) may remain unaffected (Edwards 1986; Soeprono & Rust 2004). In response to treatment, ant colonies may migrate to avoid further contact with these fast-acting insecticides, potentially leading to secondary invasions and promoting the spread of invasive ants (Buczkowski *et al.* 2005; Buczkowski 2024). Beyond such inefficiency, residual spray applications raise concerns about increased insecticide usage, which can result in runoff into urban waterways (Greenberg *et al.* 2010; Gan *et al.* 2012; Jiang *et al.* 2014) as well as increased exposure to humans, pets and other non-target organisms (Hoffmann *et al.* 2016; Sakamoto *et al.* 2019). To address these disadvantages, several alternative control strategies have been developed and evaluated, with toxic baits being the most emphasized management tool (Klotz *et al.* 1997). Toxic baits, which are insecticide-impregnated food, take advantage of ants' extensive foraging and food-sharing (i.e., trophallaxis) behaviors that facilitate bait transport into the nest and share it with nestmates (Davis & van Schagen 1993). Coupled with the delayed toxicity, the toxicant has a higher chance of reaching in-nest members including nurse workers, larvae, and even queens, leading to mortality or reduced colony reproduction (Rust *et al.* 2004). Toxic baits have since become the preferred invasive ant control method, attributed to their greater efficacy, cost-effectiveness and ease of application. The toxicants used in baits contain low doses of toxins but vary in their speed of control depending on the specific active ingredient. Taking fire ant baits as an example, Advion® fire ant bait contains 0.45% indoxacarb and results in rapid mortality within a week, while Extinguish® fire ant bait, which uses an insect growth regulator (0.5% s-methoprene) as active ingredient, takes 3–6 mo to control fire ants (Table 1).

CONVENTIONAL BAITS

An effective bait should be easy to transport and attract target ants. Consisting of attractants, carriers, sometimes additives, and active ingredients, conventional bait development focuses on testing preferences for different bait formulations (liquid, gel, granules) and the nutrient composition of food attractants (e.g., lipid, protein, and carbohydrate) to ensure the attractiveness and recruitment of target ant spe-

Table 1. Active ingredients in fire ant bait products.

Active ingredients	Mode of action	Bait trade name	Speed of control
Indoxacarb	Voltage-dependent sodium channel blockers	Advion® (0.45%)	2–7 d
Metaflumizone	Voltage-dependent sodium channel blockers	Altrevin™/Siesta™ (0.063%)	1–4 wk
Fipronil	γ-aminobutyric acid (GABA)-gated chloride channel blockers	Maxforce® FC (0.00045%)	2–6 wk
Hydramethylnon	Mitochondrial complex III electron transport inhibitors	Amdro®/Amdro Pro®/ Probait® (0.73%) Amdro® Ant Block (0.88%)	2–6 wk
Spinosad	Nicotinic acetylcholine receptor (nAChR) allosteric modulators - Site I	CONSERVE® (0.015%)	2–6 wk
Abamectin	Glutamate-gated chloride channel allosteric modulators	Ascend™/Advance™/Clinch®/Awards® II (0.011%)	2–4 mo
Pyriproxyfen	Juvenile hormone receptor modulators	Distance®/Esteem® (0.5%)	2–6 mo
s-Methoprene	Insect growth regulator	Extinguish® (0.5%)	3–6 mo
s-Methoprene + Hydramethylnon	Insect growth regulator + Mitochondrial complex III electron transport inhibitors	Extinguish® Plus (0.25% s-methoprene and 0.36% hydramethylnon) Amdro® Yard Treatment Bait (0.0172% s-methoprene and 0.036% hydramethylnon)	2–4 wk

cies. For example, sugary liquid baits attract a wide range of ants, especially those primarily feeding on liquid sugars (e.g., honeydew and nectar) such as the Argentine ant, *L. humile* (Krushelnycky & Reimer 1998; Rust *et al.* 2000). Protein- or oil-rich granular baits are most effective against the red imported fire ant, *S. invicta* and the big-headed ant, *P. megacephala* (Loke & Lee 2004; Neff *et al.* 2011). While baiting is the major strategy for controlling invasive ants, several disadvantages and limitations have been identified. First, worker ants may remain active and cause negative impacts during post-treatment period because active ingredients in baits are typically in low doses and slow-acting (Oi & Oi 2006; Klotz *et al.* 2007). Second, bait formulations are limited in use: liquid and gel baits are typically suitable for indoor use due to their relatively short lifespan under field conditions, while granular baits can be used outdoors but with reduced effectiveness after irrigation or precipitation (Klotz 2010). Advanced water-resist carriers have been proposed to overcome this disadvantage. Hydrophobic baits provide greater accessibility to foraging ants and have been evaluated and proven effective in controlling *S. invicta* and *W. auropunctata* under moist conditions (Kafle *et al.* 2010, 2015; Vander Meer & Milne 2017; Oi *et al.* 2022a, 2022b). Third, baits containing general phagostimulants may attract other non-target ant species (Zakharov & Thompson 1998). While suppressing target invasive ant species, baiting could reduce the populations of competing ants (Sakamoto *et al.* 2019). Lastly, bait acceptance may be interfered by risks perceived by foraging ants, such as the presence of toxicants or phorid flies (Orr & Seike 1998; Folgatait & Gilbert 1999; Josens *et al.* 2016; Zanola *et al.* 2024).

HYDROGEL

Hydrogels represent an innovative solution for invasive ant management, addressing the limitations of traditional liquid baits, such as fermentation, water loss, and labor-intensive maintenance (Boser *et al.* 2014). These super-absorbent bait matrices, whether synthetic or natural alginate-based, are highly attractive to invasive ants such as *L. humile* and can be deployed cost-effectively without dispensers, reducing labor and insecticide use while posing minimal risk to non-target organisms (Rust *et al.*

2015; Tay *et al.* 2017; McCalla *et al.* 2020). While *L. humile* does not always locate hydrogel baits in the field faster than other ant species in the field, they tend to occupy the hydrogels with a large number of workers and exclude other interspecific competitors (Cabrera *et al.* 2021). Despite challenges such as rapid dehydration in hot, dry conditions and incompatibility with non-water-soluble active ingredients, the hydrogel delivery system has effectively controlled several invasive ant species, including *L. humile* (Rust *et al.* 2015; Tay *et al.* 2017; McCalla *et al.* 2020; Le *et al.* 2023; Milosavljević *et al.* 2024), *N. fulva* (McCalla *et al.* 2020), *A. gracilipes* (Peck *et al.* 2017; Lee *et al.* 2025), and *Technomyrmex brunneus* (Sunamura *et al.* 2022; Terayama *et al.* 2025). Although direct efficiency comparisons between traditional bait and hydrogels are limited, Choe *et al.* (2021) demonstrated that a low-impact integrated pest management (IPM) model incorporating boric acid hydrogels is more effective at maintaining low Argentine ant densities around home perimeters than conventional spray-based treatments (Table 2). The hydrogel delivery system uses less insecticide, thereby minimizing toxicant runoff (McCalla *et al.* 2020). Additional empirical works have further demonstrated that hydrogels pose a low risk to non-target organisms, particularly pollinator insects, due to extremely low attractiveness (Buczkowski 2020; Hoffmann 2023). Several improvements have been suggested in hydrogel baits, including (1) placing the beads near irrigation point allowing them being rehydrated (Rust *et al.* 2015; Tay *et al.* 2017; Cabrera *et al.* 2021); (2) incorporating synthetic trail pheromones with hydrogel baits to increase the species-specificity (Choe *et al.* 2021); (3) adjusting the size of hydrogel beads to meet the best bait acceptance and attractiveness rate to target invasive ants (Lee *et al.* 2025); and (4) development of dry form that is easier to transport and store, to be hydrated before application (McCalla *et al.* 2020; Tay *et al.* 2020).

FORAGING DISRUPTION/ ENHANCEMENT

Ant trail pheromones, species-specific chemical compounds used for recruitment, have been studied extensively. Notable examples include (Z)-9-hexadecenal in *L. humile* (Cavill *et al.* 1979) and (Z,E)-α-farnesene in *S. invicta* (Vander Meer *et al.* 1988). Synthetic trail pheromones disrupt natural foraging by increasing turning behavior and disorientating them from natural foraging trails (Suckling *et al.* 2008, 2010, 2012; Tanaka *et al.* 2009). These trail-disrupting effects could lead to reduced foraging activity and colony food shortages, eventually resulting in population decline. However, standalone pheromone treatments show limited long-term effects (Nishisue *et al.* 2010). Greater efficacy is achieved when combined with other control methods. For example, integrating (Z)-9-hexadecenal with toxic baits or residual sprays enhances control by attracting *L. humile* to treated surfaces (Choe *et al.* 2014, 2021) or increasing bait consumption, reducing insecticide use while boosting control efficiency (Greenberg & Klotz 2000; Choe *et al.* 2014; Welzel & Choe 2016; Sunamura 2018). Similar controlling effects have been observed with pheromone-assisted liquid bait for the invasive European fire ant, *Myrmica rubra* (Hoefele *et al.* 2020). Ant pheromones not only disrupt specifically target ant species but have also been demonstrated to discriminate other non-target species, such as honey bee, reducing their contact with the toxins (Sidhu & Wilson Rankin 2016). However, the species-specific nature of pheromone-assisted technique can be a double-sword. While they effectively minimize non-target effects, their impact is limited to a single ant species. This limitation may pose challenges in areas where multiple invasive ant species coexist (Sunamura 2018).

Table 2. Comparative analysis of control methods based on insecticide reliance, cost, species specificity, and limitations.

Method	Description	Insecticide reliance	Cost (excluding labor cost)	Species specificity	Limitations
Conventional baits-granular	Solid form, distributable via dispenser, suitable for outdoor use	High	Advion: $33 per acre based on labeled application rate	Low	(1) Risk of insecticide run-off and non-target effects (2) Reduced effectiveness after precipitation (Advanced: water-resist granular baits)
Conventional baits-liquid	Liquid form, targeting sugar-loving ants, distributed by bait station, suitable for indoor and outdoor use	High	Boric acid: < $1 per home (5.6 L needed under the low-impact integrated pest management (IPM) model)[z]/$20–32 per bait station	Low	(1) Risk of insecticide run-off and non-target effects (2) Require bait station and frequent inspection and replacement, which incurs additional labor cost
Hydrogel	A controlled-release system formulated with a polymeric matrix, applicable directly without a bait station. It requires less insecticide and can be rehydrated by irrigation or precipitation	Low	$5.6 per home (5.6 L needed under the low-impact IPM model)[z]	Medium (reduced attractiveness to pollinators)	(1) Dehydration and thus reduction in attractiveness (2) Require a water-soluble active ingredient
Foraging disruption/ enhancement	Utilizes synthetic trail pheromone of the target ant species, incorporated with toxic baits/insecticide sprays to increase species specificity and reduce insecticide usage	Low	$6.16 per home (6.5 L needed under the low-impact IPM model)[z]	High	(1) Less effective when used alone (2) Limited to the target ant species only (3) Less effective for settings where multiple invasive ants co-exist
Insecticide-coated prey baits	Using live prey as an insecticide carrier enhances bait selectivity. Suitable for ant species lacking a trail pheromone system	Low	No labeled rates available but potentially high	High	(1) High labor cost (2) Need live prey
RNA interference (RNAi)	Oral delivery synthetic double-stranded RNA (dsRNA) silence target genes post-transcriptionally, highly species-specific	None	No labeled rates available but potentially high	High	Requires carriers to protect dsRNA from degradation under field conditions
Viral pathogens	Artificially inoculates a species-specific virus that causes adverse effects. The virus is sustainable in the field and can spread between colonies	None	No labeled rates available but potentially low	High	(1) Only applicable to areas where target virus is absent (2) Consider the effects of virus-induced behavioral changes on target ants

[z] Choe *et al.* (2021)

INSECTICIDE-COATED PREY BAITS

Often known as the "Trojan horse approach", prey-baiting was first proposed by Williams (1986). This method uses live prey, such as fly pupae preferred by *S. invicta*, as carriers for insecticides, facilitating horizontal transfer through worker contact or prey consumption. In empirical tests, insecticide-coated preys selectively killed only two invasive fire ant species (*S. invicta* and *S. geminata*) and a native big-headed ant, *P. morrisii*, while commercial fire ant baits negatively impacted all species tested (Williams *et al.* 1990). This highlights the advantage of prey-baiting in enhancing bait selectivity, which effectively addresses the issue of conventional toxic baits attracting a wide range of ants and/or other animals, leading to potential non-target effects. Prey baiting approach has also been explored for managing the invasive Asian needle ant, *B. chinensis*, a termite specialist that does not appear to use trail pheromone to recruit nestmates to food sources (Bednar & Silverman 2011). Studies have shown that *B. chinensis* can be effectively controlled using insecticide-coated termites, due to their strong preference for termites and their behavioral dominance over other ant species competing for the treated prey (Buczkowski 2016, 2017). Similarly, insecticide-treated termites were effective in controlling *L. humile* in environments where other ant species co-occur (Buczkowski *et al.* 2018). To develop a more practical approach for management programs based on the prey-baiting method, a recent advancement involved mimicking the effect of insect prey by coating granular baits with termite cuticular extracts (Buczkowski 2023). Insecticide-coated prey baits provide a species-specific management option that reduces non-target impacts and enhances control efficacy. This strategy is particularly valuable for invasive ant species that lack trail pheromones, where pheromone-assisted control methods are not viable.

RNA INTERFERENCE

RNA interference (RNAi) is an emerging biorational pest management tool targeting critical genes by delivering double-stranded RNA (dsRNA) that triggers enzymatic degradation of matching messenger RNA (Cooper *et al.* 2019; Taning *et al.* 2020). While a few successful cases against solitary insects exist (Singh *et al.* 2017), the application of RNAi in ant management is less common (Yan *et al.* 2020; Allen 2021). Delivering dsRNA is a major challenge for RNAi techniques in ant management due to the complexity of the food-processing system within an ant colony, which may prevent dsRNA from reaching all castes (e.g., foragers, nurses, broods, and queen) before degradation (Wang *et al.* 2016; Allen 2021). Despite limited case studies, current evidence highlights the potential of RNAi for invasive ant control. In *S. invicta*, nurse workers fed with a dsRNA-containing sucrose solution were able to transfer dsRNA to larvae, leading to molting failure and increased mortality. This was achieved through the silencing of genes involved in pheromone biosynthesis, chemosensory function, and neuropeptide signaling (Choi & Vander Meer 2012; Castillo Bravo 2015; Cheng *et al.* 2015). In *N. fulva*, a study tested dsRNA targeting six housekeeping genes, but only two of them induced significantly higher mortality compared to controls, indicating that not all housekeeping genes are equally effective targets for RNAi-based control (Meng *et al.* 2020). An innovative RNAi method was also developed for *L. humile* to silence immune-related genes in an effort to enhance pathogen transmission; however, the results showed inconsistent effects on pathogen load (Felden *et al.* 2023).

Recent advancements, such as liposome-encapsulated dsRNA, have significantly enhanced RNAi effectiveness by improving its persistence in the gut environment (Yao *et al.* 2022; Wang *et al.* 2024). For practical application, one may consider integrating dsRNA into ant baits to test if the two have synergism. However, factors such as wash-off from irrigation or rainfall, ultraviolet radiation, and microbial degradation must be addressed as these conditions can break down dsRNA before ants forage on it (Dalakouras *et al.* 2024). To tackle these issues, nanocarriers like chitosan have shown great promise for stabilizing dsRNA under field conditions (Zhou *et al.* 2023). Additionally, bacterially expressed dsRNA may offer a cost-effective alternative, with recent findings demonstrating that liposome-encapsulated bacterial and synthetic dsRNA can achieve similar levels of RNAi efficiency in different invasive ants (Meng *et al.* 2020; Wang *et al.* 2024).

VIRAL PATHOGENS

Viral infections in ants are generally chronic and asymptomatic (Baty *et al.* 2020). The three most studied viruses are likely those positive-sense single-stranded RNA viruses that infect *Solenopsis* spp. (Porter *et al.* 2015): Solenopsis invicta virus-1 (SINV-1 (Valles *et al.* 2004)), Solenopsis invicta virus-2 (SINV-2) (Valles *et al.* 2007), Solenopsis invicta virus-3 (SINV-3) (Valles & Hashimoto 2009). Instead of causing direct mortality, SINV-1 and SINV-2 infections result in reduced foraging, reduced queen weight (SINV-1) and lower fecundity (SINV-2) (Manfredini *et al.* 2016; Hsu *et al.* 2018). All these viruses are highly genus specific and replicate only in *Solenopsis* spp. (Valles 2012; Porter *et al.* 2013; Baty *et al.* 2020). Among these viruses, SINV-3 garnered significant attention for its biological control potential due to its relatively high virulence. Studies have shown that SINV-3 can cause larval and worker mortality as well as reduce queen weight and egg production (Porter *et al.* 2013; Valles *et al.* 2013, 2014). A key challenge in scaling up the field application of viral control is the development of effective virus delivery systems. Studies have demonstrated that microencapsulation techniques such as sodium alginate and hydrogels serve as effective delivery systems for viruses targeting *S. invicta* and other invasive ants including *P. megacephala* and *W. auropunctata* (Tufts *et al.* 2011; Lawrence 2024). In laboratory settings, SINV-3 has been successfully transmitted via sucrose solution and cricket debris paste (Valles *et al.* 2013). Subsequently, field studies in California demonstrated successful inoculation of fire ant populations with SINV-3 via inserting cotton-plug tubes filled with SINV-3 homogenate with sucrose solution, marking the first human-assisted establishment of SINV-3 in the field (Valles & Oi 2014; Oi *et al.* 2019). Another major challenge in microbial control of ants is often their behavioral responses to pathogens or parasites, such as avoidance, grooming, and dispersal, which potentially reduce control effectiveness due to insufficient exposure to pathogens or parasites (Oi & Pereira 1993). However, research indicates that ants do not exhibit such defensive behaviors against viral pathogens, highlighting its suitability as a microbial control agent (Oi & Valles 2009; Liu *et al.* 2025). Despite this advantage, a notable virus-induced behavioral change that warrants further investigation is the reduction in foraging intensity, which may negatively impact baiting efficiency due to inadequate bait consumption. For example, SINV-3-infected *S. invicta* colonies have shown lower levels of bait responsiveness and colony elimination rates compared to non-infected conspecifics (Liu *et al*. 2024; Liu & Yang 2024). Addressing this challenge by restoring foraging activity and improving bait uptake in virus-infected colonies could present a viable strategy to optimize the synergy between virus-based control and conventional baiting strategies. The corresponding author (unpublished data) screened various feeding-stimulating small molecules and identified several that enhance the foraging activity of virus-infected fire ants.

OTHER METHODS TO INCREASE SPECIES SPECIFICITY

Significant efforts are devoted to the development of invasive ant management tools to increase species specificity such as using ants' own chemicals (e.g., trail pheromone) to attract target ants. Venom alkaloids in *S. invicta* exhibit multiple biological activities, including roles in communication, defending, antimicrobial action, and territorial marking (Xu & Chen 2023). Incorporating venom alkaloids of *S. invicta* into baits does not affect the feeding behavior of *S. invicta* but can prevent other native ants from competing with *S. invicta*, thereby increasing species specificity (Chen 2024). A novel biorational approach involving species-specific receptor-interference (Receptor-i) approach emerged recently. The development process was initiated from screening bioactive peptides on insect Sf9 cell expressed G-protein-coupled receptors (GPCRs; receptors of neuropeptides). The target-specific GPCR agonists or antagonists were then identified (Choi & Vander Meer 2021). Receptor-i was tested on *S. invicta* targeting pheromone biosynthesis activating neuropeptide receptor (PBAN-R) by feeding assay. The peptide treatment has resulted in significant worker and queen mortality, as well as weight loss in those surviving queens (Chinta *et al.* 2023). While the Receptor-i approach against *S. invicta* is expected to have high species specificity, non-target effects have not been examined. Future assessments of Receptor-i should be conducted to determine the optimal delivery methods in the field and potential non-target effects.

SCALABLE AUTOMATED DETECTION AND TREATMENT SYSTEMS

The early detection and surveillance of invasive ants in the field are essential for rapid treatment programs but usually fall short due to their labor-intensive nature (Simberloff 2003; McLaughlin & Dearden 2019). The fire ant eradication program in Australia has integrated various aerial monitoring methods to increase the program's cost-effectiveness (Spring *et al.* 2017). Advanced automated remote detection approaches have recently been implemented by incorporating computer vision techniques and deep learning algorithms with trap stations, unmanned aerial vehicles (UAVs) or robotic dog (dos Santos *et al.* 2022; Su *et al.* 2024; Lin & Lin 2025; Monsimet *et al.* 2025). Additionally, automated aerial baiting using drones and helicopters have also been evaluated and proven to be effective in delivering granular and hydrogel baits (Hoffmann *et al.* 2023; Lin & Lin 2025). Another innovative way to enhance invasive ant detection is a citizen science program in Taiwan in which the public is encouraged to take photos of ants visiting traps consisting of potato chip lures and upload these photos to a reporting platform using a smartphone application. The photos are then analyzed by an AI image recognition system and turned into valuable observation data that facilitate the mapping of invasive ants including *S. invicta* (Lin & Lin 2025).

SYNTHESIS

In this review, we outlined novel invasive ant management strategies and their optimal applications to address different field challenges in various settings (Table 2). Recent advances in management approaches improve species specificity and reduce labor intensity, enhancing the sustainability of invasive ant control. While various tools are available, greater efforts should focus on synergizing these approaches to enhance combined efficacy and resource efficiency. For instance, integrating toxic baits, species-specific pheromones, and microbial control agents into hydrogel formulations may optimize outcomes. We also identified two critical gaps: (1) Regular monitoring of the invasive ant population dynamic is critical for implementing adaptive management strategies that respond to fluctuating population pressures and environmental conditions (Fig. 1). When invasive ants are widespread with high population densities, toxic baits are likely the most effective management tool as baits would be predominantly occupied and consumed by the invasive ants, resulting in minimal and potentially recoverable non-target effects. As invasive ant populations decline, the use of species-specific tools can further mitigate

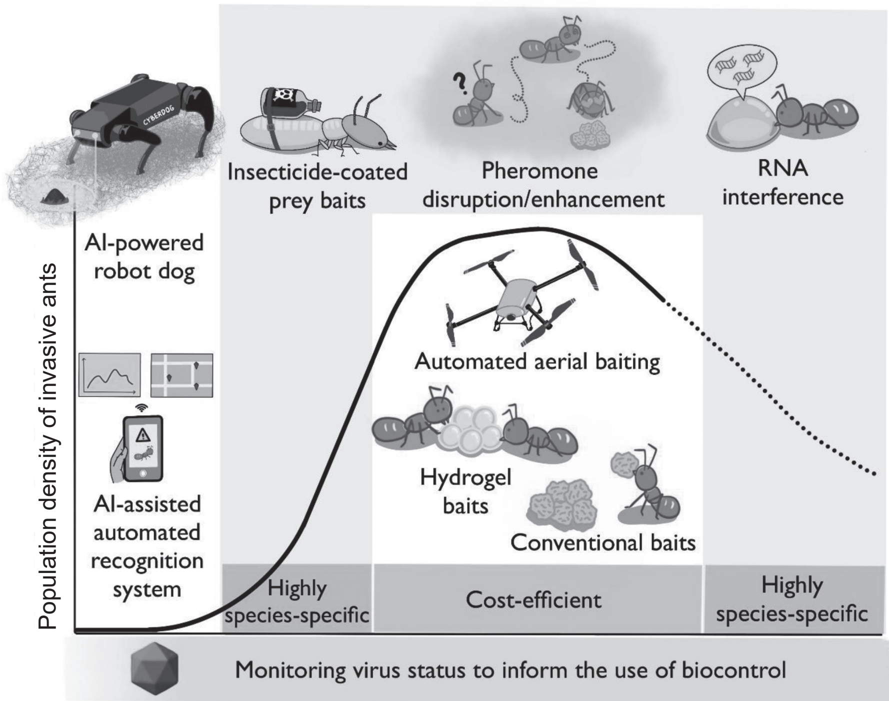

Fig. 1. Adaptive invasive ant management strategies in response to varying population densities and associated environmental conditions.

pressure deriving from non-target effects and support ecosystem recovery. (2) Understanding the often-overlooked role of microbes in ant ecology and behavior may further boost control efficiency as microbial associations can influence ant immunity, foraging, and susceptibility to additional pathogens. To conclude, integrating innovative tools with established strategies represents the key to developing a sustainable, adaptive invasive ant management framework capable of addressing future challenges.

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入侵螞蟻防治新趨勢：創新技術與精準整合策略

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摘要

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過去入侵螞蟻的防治方法主要依賴餌劑，近年相關研究則朝向更精準、永續及符合經濟效益的方向發展，致力於創新或結合更具物種專一性且環境友善的策略。本綜述著重探討可提升防治效率的新興入侵螞蟻防治方法，例如：水凝膠餌劑、物種專一費洛蒙干擾覓食或促進餌劑取食、殺蟲劑處理之天然食餌以及微生物 (病毒) 防治。此外，本篇亦討論了幾種新興技術與其應用，如 RNA 干擾技術與搭載人工智慧的監測工具。在此篇綜述中，我們概述了各種防治方法在面對不同螞蟻族群密度以及環境因子的優勢與局限性，並提供了這些創新技術如何有效整合於入侵螞蟻的管理策略中。防治人員可依據入侵螞蟻的族群密度制定防治策略，能在族群密度高峰時進行積極防治，而隨著入侵螞蟻密度降低，使用針對該入侵螞蟻的防治方法，一方面保持防治效果並同時支持生態系統恢復，既可以最大化防治效率亦可減少非目標影響。

關鍵詞：入侵螞蟻、餌劑防治、水凝膠、生物合理性防治、人工智慧。

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