Sustainable
Food Technology

ROYAL SOCIETY
OF CHEMISTRY

REVIEW

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Sustainable Food Technol.*, 2026, 4, 153

Pheromone traps: analysing the factors helpful in mitigating the use of chemical insecticides for sustainable practices in storing food product commodities

Irengbam Barun Mangang, *[a] M. Loganathan, *[b] S. Malemnganbi[c] and C. Induja[d]

Received 17th May 2025
Accepted 2nd October 2025

DOI: 10.1039/d5fb00215j

rsc.li/susfoodtech

Stored product insects, such as *Tribolium castaneum*, are responsible for significant economic losses globally by infesting grains and processed food commodities during storage. Their life cycle—from egg to larva, pupa, and adult—continues within the stored products, resulting in contamination, spoilage, and depreciation of commercial value. The use of chemical insecticides recurrently reduces the commercial value of the products. This narrative review summarizes current knowledge on pheromone-based trapping techniques for *T. castaneum*, with a focus on factors that influence trap efficacy, including trap design, environmental variables, and insect physiological states. It evaluates internal (*e.g.*, starvation, prior captures) and external (*e.g.*, airflow, lighting, surface type) parameters affecting capture dynamics, while highlighting recent innovations such as modified trap geometries and spatial mapping tools. Although aggregation pheromones show promise for monitoring, their limited dispersal and interaction with food odors restrict their utility for mass control. This review identifies gaps in trap standardization, pheromone formulation, and behavioral understanding, and recommends a shift toward integrated monitoring systems supported by IoT tools and improved trap designs. Ultimately, pheromone trapping can support sustainable pest management by reducing dependency on broad-spectrum chemical fumigants.

Sustainability spotlight

The adoption of pheromone-based trapping systems for managing red flour beetle infestations presents a sustainable alternative to chemical insecticides, aligning with eco-friendly pest control practices. By reducing reliance on synthetic chemicals, these traps help maintain the commercial value and safety of stored food products while minimizing environmental contamination and risks to non-target species. Optimizing pheromone trap efficiency through understanding internal and external influencing factors not only enhances pest management precision but also supports long-term ecological balance and food security. The integration of pheromone-based trapping technology aligns with the UN Sustainable Development Goals: SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land), emphasizing its relevance in advancing sustainable pest management, reducing post-harvest losses, and minimizing environmental and health risks associated with chemical insecticides.

1 Introduction

Stored-product pests represent a major threat to global food security by reducing the quantity and quality of stored commodities through contamination, infestation, and loss of nutritional and market value. Among these, *Tribolium castaneum* (Herbst), commonly known as the red flour beetle, is a persistent pest of global importance. Due to its small size, rapid development, and ability to thrive in a wide range of food commodities, it often spreads internationally through trade and logistics networks.[1]

To suppress infestation levels in warehouses and food storage facilities, chemical insecticides such as phosphine, deltamethrin, malathion, and pyrethrins have been extensively employed. However, long-term use has led to a growing concern regarding chemical residues, environmental impact, and the evolution of resistance in pest populations.[2] Additionally, these treatments may disrupt beneficial insect fauna, including natural predators and parasitoids such as *Cephalonomia tarsalis*, *Xylocoris flavipes*, and *Trichogramma evanescens*, thereby weakening natural pest suppression systems.

The problems addressed have emphasized the need for different preventive measures. Insect traps are one such preventive measure which has the potential for monitoring and

---

[a] College of Food Technology, Lamphelpat, Central Agricultural University, Imphal, Manipur, India. E-mail: 12barunmangang@gmail.com

[b] National Institute of Food Technology Entrepreneurship and Management, Thanjavur, Tamil Nadu, India. E-mail: logu@iifpt.edu.in

[c] College of Agriculture, Iroisemba, Central Agricultural University, Imphal, Manipur, India

[d] Biotechnology, Bharathidasan University, India

managing the stored product insects. Insect traps were initially adopted by applying sticky materials onto papers and cardboards. Probe traps, pitfall traps, two in one traps which are a combination of probe and pitfall, and light traps were some of the traps commercially available. Among these, UV light traps are particularly effective for monitoring phototactic flying insects in food-handling environments.[3] However, they lack species specificity and may unintentionally trap non-target or beneficial insects.

Semiochemicals (chemicals that mediate insect behavior) have emerged as promising species-specific alternatives. In particular, pheromones are intra-specific communication secreted by an insect to communicate with other insects of the same species.[4] There are different types of pheromones like sex, aggregate, alarm, food trail, epideictic, releaser, signal, primer and territorial.[5] However, in stored product pests research, sex and aggregate pheromones were mainly focused on. A sex pheromone is a type of semiochemical secreted by insects of one sex that causes a response in the opposite sex of the same species. Extensive research over the past two decades has explored the development, characterization, and application of pheromone-based lures for stored-product insects including *T. castaneum*.[3,6–9] The males of *T. castaneum* produce an aggregation pheromone, 4,8-dimethyldecanal (DMD), from the exocrine gland lying in the ventral side between the two fore femurs.[10] They also reported that the males with these secretions or the secretions alone attract conspecific insects of both sex groups. When both sex groups of *T. castaneum* were exposed to aggregation pheromones, there is an inhibition of ideal free habitat selection.[11]

Naturally, male *T. castaneum* locates the food and produces pheromones.[11] The female adults of *T. castaneum* move towards the pheromone searching for their partners and mates with multiple males and oviposit at the site by controlling the post-copulatory process.[12] Both male and female *T. castaneum* produce pheromones.[13] However, females produce only sex pheromones which cannot attract both sexes. Males showed a greater response to male sex volatiles (*i.e.* aggregation pheromones) when compared with female sex volatiles.[1] It was found that aggregation pheromones can be produced only by male *T. castaneum* and they can attract both sex groups.[1]

The target pheromones from male or female *Tribolium* species can be extracted only from the virgin insects of one sex by dissecting the abdominal section.[14] The abdominal parts can be transferred into a beaker for solvent extraction followed by removal of the solvent. However, synthesis of these aggregate pheromones chemically is a tedious process. Stereoisomers of 4,8-dimethyldecanal, the (4*R*,8*R*)- and the (4*R*,8*S*)- isomers (4*R*,8*R*)-DMD and (4*R*,8*S*)-DMD, respectively, can be prepared synthetically through a series of chemical reactions.[15] The prepared pheromone must properly mix with a high vapour pressure solvent before deployment.[16]

This review focuses on the application of aggregation pheromones for *T. castaneum*, emphasizing internal and external factors affecting trap performance, limitations in current trapping systems, and future directions for sustainable pest management. The review also discusses the broader implications of semiochemical-based monitoring in reducing reliance on chemical insecticides in stored-product pest control.

2 Biology and chemical ecology of *Tribolium castaneum*

The red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), is a cosmopolitan pest responsible for significant infestations in stored and processed food commodities worldwide. It thrives under high humidity (80–90%) and warm temperatures (30–35 °C), completing its life cycle in just 20–24 days. Both larvae and adults damage stored grains and grain-based products, incurring substantial economic losses.[1]

Irengbam Barun Mangang

Dr I. Barun Mangang is a young and dynamic Food Technologist. He has published more than 15 research papers and 4 book chapters, and has over 3 years of post-doctoral experience in research and academics. Presently, he is serving as Assistant Professor at the College of Food Technology, Lamphelpat, a constituent college of Central Agricultural University, Imphal, Manipur, India. He has an active h-index of 6 and an i10-index of 4 with more than 95 citations since 2020. His expertise spans over freeze-drying, radio-frequency heating, ultrasound-assisted thin bed drying, emulsification, and storage. He is an active reviewer for multiple reputed national and international journals.

M. Loganathan

Dr Loganathan Manickam handles national and international research projects on grain storage, monitoring of stored product insects and management of insects in food products. He has developed technologies for controlling psocids in grain storage and methods for thermal disinfestation of paddy using solar energy, and has developed a Solar Photovoltaic Powered Cold Storage System. He provides consultancy and handles industry projects on insect management. He has published his research findings in national and international journals and conferences. He had visited various Universities in Canada, Australia, Thailand, and UK for research collaboration and attending conferences. He guides students in the areas of Food Processing, Grain storage and pest management.

Adults secrete toxic and pungent benzoquinones from their thoracic and abdominal glands, contaminating the food and reducing its marketability.[17] This secretion not only produces a foul odor but also has the potential to trigger allergic reactions in humans. Their small size, rapid life cycle, and year-round survivability further complicate pest control measures in bulk storage environments.

Although integrated pest management (IPM) strategies are promoted, chemical insecticides are still the most widely used option due to their immediate effectiveness. However, these chemicals adversely affect not only *T. castaneum* but also beneficial predators and parasitoids such as *Amphibolus venator*, *Cephalonomia tarsalis*, *Peregrinator biannulipes*, *Trichogramma evanescens*, and *Xylocoris flavipes*, which naturally help regulate pest populations.[2]

To reduce dependence on chemical control, recent attention has focused on semiochemicals, including pheromones, which are substances secreted externally by insects to communicate with conspecifics. *T. castaneum* primarily uses aggregation pheromones—released from abdominal glands—to attract both sexes. These pheromones are species-specific and operate over short distances due to their low volatility.

While sex pheromones are common in many insect species, *T. castaneum* is primarily known for its aggregation pheromone system. Alarm pheromones, released from disturbed or dead individuals, may also influence behavior by deterring others from entering the trap area. This mix of chemical signals is essential to effective pest monitoring and trap optimization.

The behavioral ecology of *T. castaneum*, shaped by chemical cues and environmental interactions, lays the groundwork for alternative pest management strategies. Understanding how these pheromones are produced, perceived, and manipulated is critical for designing pheromone traps and for reducing reliance on chemical insecticides.

3 Fumigation and resistance issues

Fumigation remains one of the most widely used strategies for managing stored-product insect pests, including *Tribolium castaneum*, due to its rapid knockdown effect and penetrative ability in bulk grain masses. Phosphine is currently the most prevalent fumigant globally, favored for its cost-effectiveness and ease of application. However, overreliance on this chemical has led to an alarming rise in phosphine resistance among pest populations, including *T. castaneum*.[18]

The development of resistance is a multifactorial process, influenced by the frequency and dosage of application, environmental conditions, and the physiological adaptations of the pest.[19,20] Resistant populations often exhibit increased detoxification enzyme activity, reduced cuticular penetration, and altered respiration rates—mechanisms that confer survival advantages even under lethal exposure levels.[21] As a result, traditional dosages are no longer effective in suppressing resistant colonies, prompting increased application rates and prolonged fumigation cycles, which in turn pose greater health and environmental risks. Moreover, sublethal exposure to fumigants has been shown to alter insect behavior, potentially influencing trap efficacy and pheromone responsiveness. In some cases, fumigated adults exhibit reduced mobility and altered pheromone production, which may interfere with post-treatment monitoring strategies that rely on trap captures as indicators of residual infestation levels. The logistical challenges of sealing large storage structures and the lack of uniform gas distribution during fumigation also reduce treatment efficacy. Furthermore, fumigants provide no residual protection, making reinfestation likely if sanitation and monitoring measures are not rigorously followed.

In light of these challenges, there is a growing consensus that fumigation should no longer be the sole line of defense. Instead, it should be integrated with alternative methods such as temperature treatments, controlled atmospheres, biological control, and semiochemical-based monitoring systems. Such integrated approaches can help delay resistance development, reduce chemical residues in food systems, and promote more sustainable long-term pest management solutions.

4 Pheromone traps – mechanism and application

Pheromone traps are species-specific monitoring tools designed to attract insects using semiochemicals—typically aggregation pheromones in the case of *Tribolium castaneum*. These traps offer a non-invasive and chemical-free approach to assess pest presence, population trends, and spatial distribution in food storage environments.

In *T. castaneum*, the aggregation pheromone consists primarily of 4,8-dimethyldecanal, a volatile compound produced by males and attractive to both sexes.[10] This pheromone is typically formulated and integrated into lures placed inside traps such as pitfall traps, storgard dome traps, and corrugated floor traps. These designs are often baited with a combination of pheromones and food-based kairomones to enhance attractiveness.

The mechanism involves insects being drawn to the odor plume emitted by the lure. Upon arrival, the beetles fall into the trap well or adhesive surface and are retained. Trap placement plays a critical role in effectiveness. Traps are most effective when placed near infestation sources, along walls, or in undisturbed areas with minimal airflow disruption. Environmental conditions such as temperature, humidity, and air currents influence the dispersal of the pheromone plume and consequently the success of captures.[22]

Pheromones provide a highly effective tool for stored product protection as they can be used to detect or monitor the specific species present in storage.[23] Continuous monitoring helps to detect the location and level of infestation. Mass trapping of insects using pheromones has also been found effectively possible in many lab studies.[24,25] In this context, the use of pheromones as a tool in IPM strategies is highly applicable. Hence, it can be deduced that insect communication is an interesting part of entomology where it can either be used to benefit humans or to appreciate the laws of nature.

Advancements in trap design, controlled-release matrices, and multi-modal lures continue to improve the reliability and practicality of pheromone traps in commercial storage settings. However, further research is needed to standardize protocols for interpretation of trap data and correlate it with actual infestation severity.

5 Factors affecting trap performance

The efficiency of pheromone traps for *Tribolium castaneum* is not solely determined by the presence of lures but is modulated by a complex interplay of internal and external factors (Fig. 1). Internal factors include the status of insects like whether the insects were food deprived, dead or previously captured (Table 1). External factors include chemicals applied like whether the traps were placed in a fumigated area, climatic conditions, trap distance, trap design, trap colour, shape and air flow, pest density, and presence of flour (Table 2). Understanding these parameters is crucial for interpreting trap catch data and for designing robust monitoring programs.

5.1. Internal factors

5.1.1. Effect of previous capture. The accumulation of dead insects in traps has been shown to reduce *T. castaneum* captures. This is attributed to the release of alarm pheromones or other decay-associated volatiles that act as repellents. Even when an aggregation pheromone is present, the deterrent cues from dead conspecifics can override attraction, decreasing trap efficacy. The trap baited with or without the aggregation pheromone is influenced by the presence of accumulated samplings which were trapped. This has been observed in traps containing alive insects and in traps with dead insects. The result showed that the presence of dead specimens in a trap baited with or without 4,8-dimethyldecanal has repelling behaviour leading to reduction in trap capture. This relates to the presence of residual alarm pheromone produced by the insects before their death.[26]

In contrast, the presence of live or freshly captured conspecifics can increase trap attractiveness. This is especially true when the trapped individuals are emitting aggregation pheromones, which reinforce group-level attraction (Athanassiou *et al.*, 2016). Experiments show that the probability of entry increases when traps already contain actively signaling beetles of the same species—suggesting positive social feedback rather than deterrence. When the traps were seeded with the opposite species, there was no increase in beetle captures for both *T. castaneum* and *T. confusum*. There is an increase in the capture of insects in the trap of two species when only one species was released, whereas when both species were released the influence of the pheromone was less. The presence of beetles in the trap can be influenced by the response of beetles to the nearby traps. The capture of *T. castaneum* and *T. confusum* tends to increase beetle captures in traps baited with pheromones and food oil. The trap response of a given species can be moderated by the presence of another species in the same arena. The relationship between the trap catch and actual insect density may vary. The species spectrum and population density that are recorded through the trapping may be different than the actual spectrum as described by Athanassiou and Kavallieratos.[27]

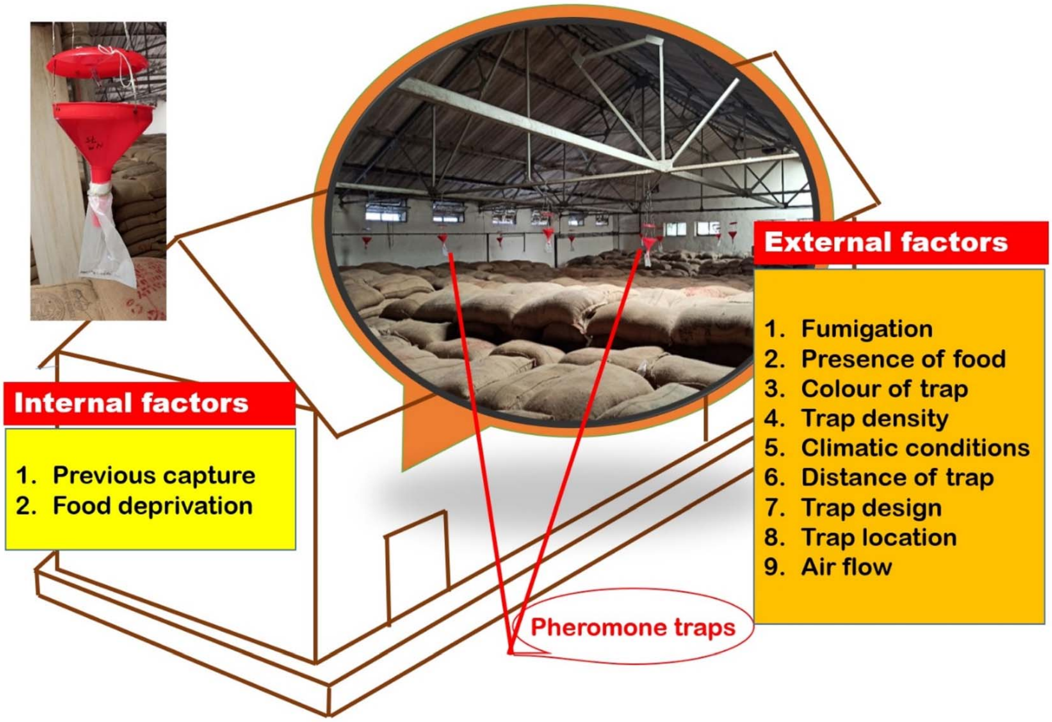

Fig. 1 Internal and external factors affecting the capture efficiency of *Tribolium castaneum* in storage facilities.

Table 1 Internal factors influencing capture of *T. castaneum* by pheromone traps

Internal factors	Findings	References
Effect of previous capture	The capture of *T. castaneum* was significantly increased when there is previous capture	Athanassiou, Kavallieratos[27]
Food deprivation	Starved pests moved slower towards the pheromone than well fed pests	Romero, Campbell[28]

5.1.2. Food deprivation. The ability of insects to detect resource patches from a distance can be influenced by many factors. Two factors that might influence search behaviour are directional air movement (an exogenous factor) and food deprivation (an endogenous factor). The beetles respond to cues associated with air movement. When air is moving the proportion of beetles locating the flour patch will be more. In regard to food deprivation, a greater proportion of the food-deprived beetles are in the flour patch than those that had not been deprived because the beetles would be hungry, or in search for the oviposition site. Food deprivation had no significant effect on the amount of time that the beetles spent in the area as reported by Romero and Campbell.[28]

Research has shown that starvation alters the beetle's behavioral thresholds, making even weak olfactory cues sufficient to trigger movement toward a source.[13] This increased sensitivity can be advantageous for trap performance, especially in low-infestation environments.

While airflow can facilitate odor dispersal, it is the beetle's internal physiological state—such as hunger—that largely determines its decision to orient and commit to a stimulus. Therefore, when deploying traps, consideration of the pest's feeding history and local food availability is important for interpreting variability in trap captures and behavioral assays.

5.2. External factors

5.2.1. Fumigation. Understanding the impact of fumigation and the mortality response of stored product insects helps in managing their infestation. An extremely potent fumigant for disinfestation of bulk stored grains and other food commodities is phosphine gas deployed as tablets. The continued misuse of phosphine such as short exposure times at high temperatures or fumigation in poorly sealed enclosures has contributed to the development of phosphine-resistant strains of *T. castaneum* across the globe. These leads to development of some resistant strains all over the world.

Campbell and Toews[29] explain that the fumigation done in mills showed good signs of an average effect of treatment and is compatible for other studies. *T. castaneum* adults present in the mill after fumigation could result from nonmutually exclusive general mechanisms like the survival of treatment within structure or movement into structure after treatment. In those mills, insect survival evidenced a failure of fumigation as the fumigation treatment may not have reached the target gas concentration and time (CT). The other case is that the target CT was inadequate to cause 100% death in tested populations. These chemicals are effective but their resistance has already been developed in *T. castaneum*.[19,20] Fumigation efficacy is typically assessed using pheromone traps in two ways: (1) by measuring the immediate reduction in adult *T. castaneum* captures following treatment, and (2) by tracking the rate of rebound in beetle captures over time, which may indicate surviving populations or reinfestation. This dual approach provides insights into both the short-term and longer-term effectiveness of fumigation.

Table 2 External factors influencing capture of *T. castaneum* by its pheromone trap

External factors	Findings	References
Fumigation	Trap catches reduced by 84.6 ± 4.6% after fumigation	Campbell and Toews[29]
Presence of flour	*T. castaneum* adults spent similar amounts of time in the release site 8 cm and 16 cm away from the trap	Romero and Campbell[28]
Colour of trap	The number of *T. castaneum* captured in a black trap was more than that in a white trap	34
Trap density	Increasing the number of traps employed does not have a significant impact on the mean capture of *T. castaneum*	Buckman and Campbell[36]
Climatic conditions	Trap catches during winter were relatively low	Daglish and Ridley,[37] Rajan and Muralitharan[38]
Distance of the trap	The pheromone baited trap was most effective at the shortest distance tested (30 cm)	Dissanayaka and Sammani[7]
Trap design	The pitfall trap was more effective than the sticky trap	Phillips and Doud[3]
Shape and air flow	The square pitfall trap with a fan has the highest efficiency (65.38%)	Sajeewani and Dissanayaka[39]

The measurement of rebound patterns was highly variable and also showed the impact of many diverse factors in population growth. The prospects of different factors cannot be tested independently, so the data in different ways can be analyzed. The analysis handled by Campbell *et al.* in 2010 showed a positive correlation between the number before and number after fumigation. The potential of reduction after fumigation is proportional to the number of beetles present and there is no reduction to the baseline level. It also controlled the densities reached before treatment. After fumigation, the movement of *T. castaneum* in the storage facilities was quite significantly lowered even if the insects become resistant to fumigants, leading to low captures in the pheromone trap.[30,31]

5.2.2. Presence of food baits. Stored product insects depend on food supplies available in storage for their survival. The movement behaviour of insects is an interesting area of research. A male *T. castaneum* locates/finds the food commodity and in turn secretes its pheromones leading to attraction of females. A question that arises during the deployment of traps is whether the presence of the food baits has an impact on the capture of the insects. Although some studies have shown that wheat flour odours can enhance trap captures of *T. castaneum*,[32] other research indicates that food odors alone are often unreliable as attractants due to inconsistent behavioral responses under field conditions.[33,34]

The searching behavioural patterns represent the conflux of three factors namely the environmental characteristics and the ability of an insect; external environmental factors to determine resources availability and intrinsic risk; and internal factors (deprivation or sexual receptivity). The behaviour of searching pattern of insects can be controlled by the flexibility in response to internal and external environmental factors. The flexibility is indicated in discontinuous and continuous variability, and permits the monotonic adaptation to assist some factors. Insects use the resource evaluation and all information channels in their search. The insects get triggered when exposed to food odours due to the sensory information perceived from the external environment and internally stored genetic information.[35]

5.2.3. Colour of trap. The movement of insects also depends on colour perceived by them. Insects in general are attracted by coloured objects because of their specific reflectance that stands out in a contrasting background.[34] In order to mimic the conditions of the actual events, numerous experimental setups have been used. The mimics were simpler versions and prototypes of the complexity from the actual events. Trap color influences beetle behavior by enhancing visual contrast in storage environments. Several studies have observed that *T. castaneum* adults show a consistent preference for dark-colored surfaces, especially black, likely due to higher visual contrast.[34,40] However, color preference may also vary by developmental stage, with larvae sometimes responding differently from adults. These color effects should be considered in trap design, although their contribution is secondary to pheromonal cues.

5.2.4. Trap density. An important component of pest management is to understand the spatial and temporal potent of insect populations. The sampling of insect population especially at low density made it difficult to solve the problem. Traps can be used to attract the insect and to improve detection in spite of population being scattered. To determine the optimal trap density, the stability between the fundamental biology of *T. castaneum* and applied and commercial considerations including ability, type, economic costs and simultaneous pest management practices was studied.[36] The beetle density was estimated to be less than 5% on average suggesting that pheromone traps yield the most accurate density. The trap densities of 0.01–0.06 m^2 have been successfully used in long term monitoring studies for operating flour mills in USA. Campbell and Toews[30] suggested that an increase in trap density might be feasible in other facilities.

Trap density plays a crucial role in accurately monitoring *T. castaneum* populations, especially in large and structurally complex facilities. Studies have shown that low-density trapping (*e.g.*, <0.06 traps per m^2) can still yield reliable data when strategically distributed.[36] However, interpreting trap data also requires understanding spatial dynamics and pest movement behavior.[41] Tools such as contour mapping[42] have been effectively applied to visualize infestation hotspots. Additionally, long-term deployment in combination with spatio-temporal modeling improves the ability to detect changes in pest distribution post-treatment.[27,43]

5.2.5. Climatic conditions. Rajan and Muralitharan[38] described the seasonal flight pattern in the bulk grain stored areas using both beetles (*Tribolium castaneum* and *Rhyzopertha dominica*). The seasonal flight pattern of *T. castaneum* differs from that of *R. dominica* regarding the trapping efficiency. The trap catches of *T. castaneum* adults by multidirectional flight trap baited with aggregation pheromones showed that this insect flies throughout the year in southern India, whereas the flight was seasonal in northern India where it is too cold for flight in winter, <20 °C, in New Delhi. The number of insects trapped across the agricultural land in the north was restricted from July to October (warmer months).

Recent studies have further shown that environmental factors such as temperature, airflow, and humidity significantly influence insect responsiveness to semiochemicals, including pheromones. *T. castaneum*'s orientation and attraction to pheromone traps diminish under suboptimal climatic conditions, underscoring the need to tailor monitoring strategies to local temperature and humidity profiles.[44]

5.2.6. Pest population density. The efficiency and interpretation of pheromone trap data are closely tied to the underlying pest population density. At low densities, *T. castaneum* may encounter traps less frequently, making early detection challenging. Conversely, at high densities, traps can become saturated or may not linearly reflect actual population trends due to behavioral saturation and competitive interactions.[45] Buckman and Campbell[36] demonstrated that increasing pest density leads to diminishing marginal returns in trap captures, possibly due to physical crowding at trap entrances or repellence from alarm pheromones released by trapped individuals. They emphasized that while traps are sensitive even at low densities, trap interpretation must consider biological noise and density-dependent movement behavior.

Romero and Campbell[28] further highlighted that crowding or starvation can modify insect search patterns, leading to variability in responsiveness to both pheromonal and kairomonal cues. In high-density scenarios, interspecific competition and mating pressure may also reduce responsiveness to synthetic pheromones in traps. Moreover, Athanassiou and Kavallieratos[27] found that the presence of other conspecifics in the trap (*i.e.*, prior captures) may alter beetle behavior, sometimes enhancing and other times reducing trap entry, depending on the sex ratio and environmental cues.

Therefore, to improve accuracy in monitoring programs, pest population density should be factored into both trap deployment strategy (*e.g.*, spacing and frequency) and data interpretation. In large storage environments, combining trap data with direct sampling or contour mapping[42] may yield more robust estimates of population structure and infestation severity.

5.2.7. Trap distance. The adult response towards pheromone- and kairomone-baited traps is influenced by various factors including the distance from the attractant source, air movement, and insect behavioral variability. Under still-air conditions, the effective attraction range of pheromone plumes is greatly reduced; however, when airflow is present, attractants can be perceived from much greater distances, increasing the likelihood of successful trap encounters.[7,35]

A recent study by Harman and Morrison III[26] compared the effectiveness of different trap types and attractant combinations in commercial food processing facilities in Greece. The findings emphasized that trap performance varied significantly with deployment location and airflow patterns. Specifically, airflow not only affected the dispersion range of semiochemicals but also modulated beetle activity and orientation behavior. This reinforces the importance of aligning trap positioning with air circulation zones to optimize semiochemical delivery and capture efficiency.

Therefore, both airflow direction and spacing between traps are critical operational parameters in large-scale facilities. Traps should be positioned to maximize plume spread without overlap or interference, particularly when using aggregation pheromones with relatively short-range dispersal.

5.2.8. Design of the trap. A trap was developed by DeCoursey[46] for entrapping *Tribolium confusum* without the use of pheromones. The research incorporated different food attractants in a corrugated paper and the effectiveness was up to a short distance. With the identification of a pheromone, the effectiveness of the trap was increased.[47,48] The most familiar traps like pitfall traps and sticky traps were designed to adopt in the field for capture of field insects.[49,50]

Barak and Burkholder[51] developed a storgard trap by incorporating a plastic pitfall which contained a food bait having insecticidal and attractant properties. The trap is made from a rectangular corrugated board by folding to form four layers. The first, second and third layers had a round hole which can hold the cup. The second and third layers were cut to form four V shaped openings in each layer. This allowed free movement of the insects. Mullen[52] compared its effectiveness to his very own Savannah trap in trapping *T. castaneum*. He described that the storgard trap lacks an entrapping mechanism. A base with a sticky bottom was provided for entrapping the insects. The insects entered through the slit openings, climbed through the rough surface and fell down the smooth surface searching for the pheromone and got trapped by falling in the hole.

Several commercial sticky traps have been adopted for trapping *T. castaneum* with modifications from the previous traps like addition of caps to prevent dust accumulation in the sticky parts.[3,53] A commercial funnel trap developed by Cogan and Hartley[54] to capture stored product moths is also a modified version of a savannah trap. Endeavors for effective trap design (Fig. 2) can also be seen in recent years.[3,7,27,39,55]

5.2.9. Shape and air flow. One of the most important abiotic factors that impact on the ability of insects that orient towards the attraction source is air movement. *T. castaneum*'s response to pheromone/kairomone baited traps was influenced by the presence of air moving over the trap towards the beetle. The beetles are able to use directional information from air movement to locate the attractant source, but they did not respond to the non-directional cues. Under airflow conditions, the active space around the trap extended out to the maximum tested distance of 90 cm. The air movement of *T. castaneum*'s response to traps has important implications because of commercial food facilities which have complex environments with considerable variations among the trap locations under physical and environmental conditions and in wind speed and direction.[35]

Sajeewani and Dissanayaka[39] explain that in the modified storgard trap, the direction of corrugations in adjacent layers changes to maintain the higher amount of pheromone inside the trap and get more insects oriented into the cups. The rectangular (Fuji trap) and cone shaped (Flit-Trak) traps were ramp and pitfall type and increased trapping as 26 and 23 percentage. The ramp of these two traps caused increased trapping. Different shapes would also have increased trapping efficiency. The factors associated with improved performance include differences in shape, rougher entry surfaces, placement of pheromone/kairomone within the trap, covered trap tops, and forced ventilation from an internal fan. The newly designed traps can be tested by enhancing the potential use of these traps in stored-product pest management.

6 Spatial distribution of *T. castaneum* and pheromone trap data

Understanding the spatial and temporal distribution of *Tribolium castaneum* in storage environments is critical for interpreting pheromone trap data and improving pest management. In storage facilities, *T. castaneum* populations tend to be aggregated, with certain locations consistently yielding higher trap catches (infestation "hotspots"). For example, early work by Arbogast and Kendra[42] in retail stores used spatial trapping maps to pinpoint localized beetle concentrations. Long-term monitoring in flour mills further shows that trap captures exhibit strong temporal dynamics: populations often peak

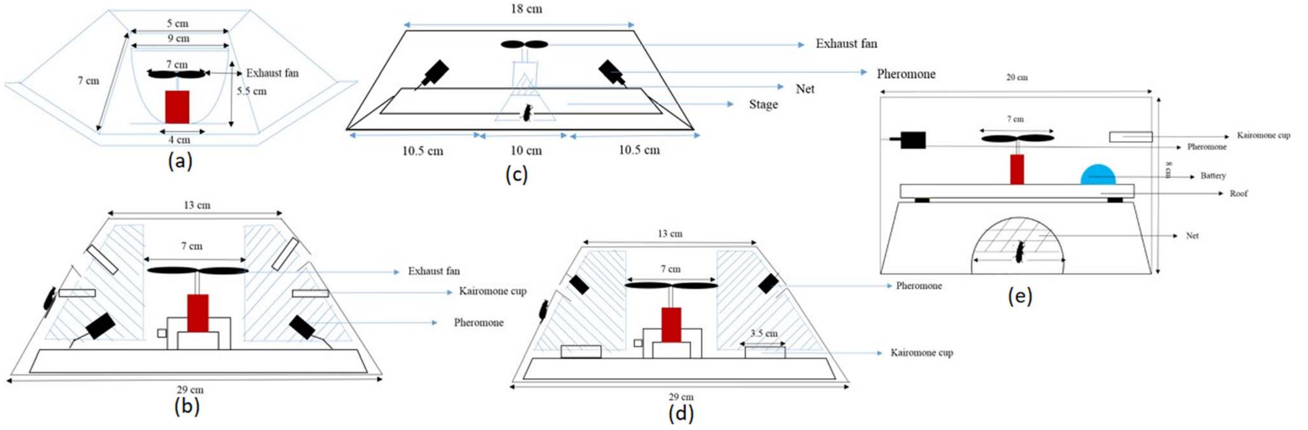

Fig. 2 Pitfall style dome traps which have a hexagonal shape (a), triangular shape (b–d) and square shape (e).[39]

during warmer seasons and decline in colder periods or after interventions. In two U.S. mills, pheromone trap catches increased between monitoring periods as temperatures rose, but dropped by 70–85% immediately following fumigation, underscoring both seasonal growth and short-term suppression from treatment. These patterns highlight why both space and time must be considered when analyzing trap data.

Spatial analysis tools enhance the interpretation of pheromone trap captures. Techniques like contour mapping have been effectively applied to visualize pest distribution and identify infestation hotspots from trap count data. Arbogast and Kendra[42] and Campbell and Mullen[45] demonstrated that mapping trap counts can guide the design of efficient monitoring grids and optimize the timing and location of interventions. By overlaying trap catch data on facility blueprints, managers can see where beetles are most active. Such spatial mapping, especially when combined with statistical modeling, also allows tracking of infestation changes over time – for instance, verifying a drop in captures after a fumigation or detecting a rebound weeks later. Spatio-temporal analyses thus provide a more nuanced understanding of pest movement patterns than raw trap numbers alone.

There are several practical applications of spatial trap data for pest monitoring and control. Pheromone trap networks enable targeted interventions by revealing when and where to focus control efforts. For example, a multi-mill study by McKay and Bowombe-Toko[8] concluded that trap catch patterns could be used to decide when and where to apply treatments, helping mill managers pinpoint the most vulnerable spots in a facility. Trap-derived maps of beetle activity often guide localized actions like directed insecticide applications, sanitation measures, or sealing of entry points around hotspot areas. Trap data are also increasingly used to evaluate treatment efficacy. Doud and Cuperus[31] showed that monitoring trap catches before and after fumigation can reveal incomplete pest suppression – in their study, fumigations significantly reduced *T. castaneum* trap counts, but captures shortly afterward indicated that populations were not fully eliminated and may have rapidly rebounded or migrated from untreated zones. This kind of insight is invaluable: it can confirm whether a fumigation or fogging worked and how long its effects last. Overall, continuous spatio-temporal monitoring supports an IPM approach by indicating if and when localized treatments are necessary. Recent field research in fact confirms that trap-based spatial surveillance can substantially reduce reliance on whole-facility fumigations, by enabling more precise, limited-area pest control measures.[56] In fact, pheromone traps serve as early-warning sensors across a facility, directing attention to trouble areas and allowing pest managers to act preventively rather than reactively.

However, several limitations and considerations must be kept in mind when using spatial analysis of trap data. Pheromone trap counts reflect relative pest activity, not the absolute population. Many studies show that trap capture numbers do not always correlate well with true infestation levels.[41] Traps are excellent for detecting presence/absence and trends, but they provide an index of pest density rather than a precise count.[31] Thus, interpreting trap data should involve thresholds or changes over time, and when possible, should be supplemented with direct sampling to estimate actual population size.

Local conditions within a facility can skew trap captures and must be considered in spatial analysis. For instance, a detailed mill study found significantly more *T. castaneum* in traps placed near milling equipment, where higher temperature and flour dust accumulation created favorable microhabitats.[34] Such environmental factors (heat, food debris, shelter) can create apparent hotspots. At the same time, broad temporal fluctuations often overlay these patterns – the same study noted that temporal variation in beetle activity often overwhelmed the influence of static site features. In other words, a hotspot one week may dissipate the next if conditions change or the population moves, so spatial patterns are not fixed.

Obtaining meaningful spatial maps requires deploying a sufficiently dense grid of traps. Spatial analyses like contour mapping generally need a large number of data points for accuracy.[41] If traps are too sparse, true infestation centers can be missed. Additionally, the aggregation pheromone of *T. castaneum* (4,8-dimethyldecanal) has a limited dispersal radius;

studies indicate its attractive range is on the order of only a few meters or less. This short range means traps only sample a small area – so to effectively detect all foci, traps must be placed relatively close together or in sufficient numbers to cover the space. Poor trap placement or low trap density can lead to blind spots in the spatial data.

T. castaneum behavior can also introduce biases in trap-based measurements of spatial distribution. Laboratory arena experiments showed that red flour beetles do not roam uniformly; they tend to accumulate in certain areas (*e.g.* room corners or beneath shelving), which is where most traps in those tests made captures.[41] In the field, beetles may follow wall edges or stay near food patches, so trap placement relative to these features will affect catches. Moreover, traps can become less effective at high pest densities due to saturation or deterrence. If a trap contains many dead or dying conspecifics, it can repel incoming beetles *via* alarm odors or physical blockage. Indeed, prior research observed that the presence of dead insects in a trap or an excessive number of captures can either discourage additional beetles from entering or simply reflect that the trap has reached capacity. These behavioral nuances mean that spatial trap data must be interpreted with caution – an area with fewer captures might be truly low in insects, or it might be that insects avoided traps due to competitive or repellent cues. Careful attention to trap maintenance (*e.g.* removing dead insects, refreshing lures) and understanding pest behavior (such as their tendency to harbor in refugia) are important when analyzing the spatial patterns.

By acknowledging these considerations and combining trap data with other information (*e.g.* visual inspections, product sampling, and knowledge of facility layout), pest managers can more reliably interpret pheromone trap results. Spatial analysis of trap captures, despite its limitations, provides a powerful decision-support tool for stored-product IPM: it helps locate infestation foci, track population trends after control actions, and ultimately enables more timely and targeted interventions.[31,56] This integrated use of pheromone trapping and spatial monitoring can improve the efficiency of pest control in storage facilities while minimizing unnecessary chemical treatments, aligning with the goal of sustainable pest management.

7 Constraints, gaps and future directions

Several technical and logistical challenges must be addressed, including the optimal shape and size of traps, the pheromone concentration required for maximum efficacy, and the effective range in terms of both distance and height. Due to their volatile nature, pheromones must be maintained at appropriate concentrations to ensure long-term viability. To sustain their release over extended periods, these semiochemicals may need to be incorporated into controlled-release or encapsulated formulations, which can enhance the efficiency of mass trapping and mating disruption strategies against *T. castaneum*. While pheromone-based trapping has proven effective for detection, several constraints limit its operational utility for *T. castaneum*: short-range dispersal of aggregation pheromones reduces detection radius, especially in cluttered environments; interference from food odors, competing volatiles, and air currents can reduce signal fidelity; lack of integration with real-time decision systems limits responsiveness and undercuts proactive pest management.

Furthermore, much of the existing research focuses on trap color, height, and design in isolation. There is a pressing need to understand interactive effects—*e.g.*, how airflow interacts with trap geometry and behavioral states like starvation. Contrary to concerns that mass trapping may be insufficient for *T. castaneum*, enhanced monitoring using optimized traps can support threshold-based interventions (*e.g.*, localized fogging, heat treatment, or sanitation efforts), reducing the need for blanket fumigation.

Future directions should include: development of multimodal lures combining pheromones with kairomones or microbial volatiles; controlled-release formulations that sustain signal strength in dusty or humid conditions; integration with IoT sensors for automated population tracking and early warning systems; field validation of new trap prototypes (including fly traps) under diverse facility conditions. These strategies, together with a systems-level pest monitoring approach, can help transition from reactive to predictive stored-product pest management. Furthermore, despite their potential, tactics like mass trapping and mating disruption are still not well studied for *T. castaneum* due to challenges with large-scale field application and synthetic pheromone generation. Developing integrated pest control strategies to combat this widespread stored-product pest requires addressing these limitations. The use of chemical insecticides will be significantly decreased when pheromones are used.

Author contributions

All authors contributed to the study conception and design. Conceptualization and proofreading were done by Dr M. Loganathan. The first draft was written by Dr I. B. Mangang who also conducted review, material preparation, and conceptualization. Proofreading and review were done by S. Malemnganbi. Dr C. Induja helped in formatting and writing.

Conflicts of interest

The authors report no conflict of interest.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Acknowledgements

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript. The authors would like to thank NIFTEM-T for support.

References

1 P.-O. C. Olsson, C. Ryne, R. Wallen, O. Anderbrant and C. Löfstedt, Male-produced sex pheromone in Tribolium confusum: behaviour and investigation of pheromone production locations, *J. Stored Prod. Res.*, 2006, **42**(2), 173–182.

2 D. Hagstrum and B. Subramanyam, *Stored-product Insect Resource*, Elsevier, 2017.

3 T. W. Phillips and C. W. Doud, Responses of Red Flour Beetle Adults, Tribolium castaneum (Coleoptera: Tenebrionidae), and Other Stored Product Beetles to Different Pheromone Trap Designs, *Insects*, 2020, **11**(11), 733.

4 N. M. Abd El-Ghany, Pheromones and Chemical Communication in Insects, *Pests, Weeds and Diseases in Agricultural Crop and Animal Husbandry Production*, 2020, pp. 1–13.

5 N. B. Khondkhodjayeva, An Ecological Significance Of Pheromones, *Theor. Appl. Sci.*, 2019, (9), 85–87.

6 I. B. Mangang, A. Tiwari, M. Rajamani and L. Manickam, Comparative laboratory efficacy of novel botanical extracts against Tribolium castaneum, *J. Sci. Food Agric.*, 2020, **100**(4), 1541–1546.

7 D. Dissanayaka, A. Sammani, L. Wijayaratne, T. Bamunuarachchige and I. I. I. W. Morrison, Distance and height of attraction by walking and flying beetles to traps with simultaneous use of the aggregation pheromones from Tribolium castaneum (Herbst)(Coleoptera: Tenebrionidae) and Rhyzopertha dominica (F.)(Coleoptera: Bostrychidae), *J. Stored Prod. Res.*, 2020, **89**, 101705.

8 T. McKay, M. Bowombe-Toko, L. Starkus, F. Arthur and J. Campbell, Monitoring of Tribolium castaneum (Coleoptera: Tenebrionidae) in rice mills using pheromone-baited traps, *J. Econ. Entomol.*, 2019, **112**(3), 1454–1462.

9 L. Kheloul, A. Kellouche, D. Bréard, M. Gay, C. Gadenne and S. Anton, Trade-off between attraction to aggregation pheromones and repellent effects of spike lavender essential oil and its main constituent linalool in the flour beetle Tribolium confusum, *Entomol. Exp. Appl.*, 2019, **167**(9), 826–834.

10 D. Faustini and D. Halstead, Setiferous structures of male Coleoptera, *J. Morphol.*, 1982, **173**(1), 43–72.

11 W. D. Halliday and G. Blouin-Demers, Male aggregation pheromones inhibit ideal free habitat selection in red flour beetles (Tribolium castaneum), *J. Insect Behav.*, 2016, **29**(4), 355–367.

12 C. Gasparini and J. P. Evans, Female control over multiple matings increases the opportunity for postcopulatory sexual selection, *Proc. R. Soc. B*, 2018, **285**(1888), 20181505.

13 T. Y. Fedina and S. M. Lewis, An integrative view of sexual selection in Tribolium flour beetles, *Biol. Rev.*, 2008, **83**(2), 151–171.

14 N. Subekti, R. Saputri and T. Kartika, Dimethyldecanal Analysis on Body Extract and Head Space Sampling Method, *J. Phys.: Conf. Ser.*, 2020, **1567**, 042069.

15 F. Verheggen, C. Ryne, P.-O. Olsson, L. Arnaud, G. Lognay, H.-E. Högberg, *et al.*, Electrophysiological and behavioral activity of secondary metabolites in the confused flour beetle, Tribolium confusum, *J. Chem. Ecol.*, 2007, **33**(3), 525–539.

16 R. Mankin, K. Vick, M. Mayer, J. Coffelt and P. Callahan, Models for dispersal of vapors in open and confined spaces: Applications to sex pheromone trapping in a warehouse, *J. Chem. Ecol.*, 1980, **6**(5), 929–950.

17 T. A. El-Desouky, S. S. Elbadawy, H. B. Hussain and N. A. Hassan, Impact of insect densities Tribolium Castaneum on the benzoquinone secretions and aflatoxins levels in Wheat flour during storage periods, *Open Biotechnol. J.*, 2018, **12**, 104–111.

18 G. Opit, T. W. Phillips, M. J. Aikins and M. Hasan, Phosphine resistance in Tribolium castaneum and Rhyzopertha dominica from stored wheat in Oklahoma, *J. Econ. Entomol.*, 2012, **105**(4), 1107–1114.

19 R. Malekpour, M. A. Rafter, G. J. Daglish and G. H. Walter, The movement abilities and resource location behaviour of Tribolium castaneum: phosphine resistance and its genetic influences, *J. Pest Sci.*, 2018, **91**(2), 739–749.

20 R. Ramya, C. Srivastava and S. Subramanian, Monitoring of phosphine resistance in Indian populations of Tribolium Castaneum (Herbst) from stored wheat, *Indian J. Entomol.*, 2018, **80**(1), 19–23.

21 H. Benhalima, M. Chaudhry, K. Mills and N. Price, Phosphine resistance in stored-product insects collected from various grain storage facilities in Morocco, *J. Stored Prod. Res.*, 2004, **40**(3), 241–249.

22 A. A. Semeao, J. F. Campbell, R. J. Whitworth and P. E. Sloderbeck, Influence of environmental and physical factors on capture of Tribolium castaneum (Coleoptera: Tenebrionidae) in a flour mill, *J. Econ. Entomol.*, 2012, **105**(2), 686–702.

23 M. C. Larsson, Pheromones and other semiochemicals for monitoring rare and endangered species, *J. Chem. Ecol.*, 2016, **42**(9), 853–868.

24 B. Stevenson, L. Cai, C. Faucher, M. Michie, A. Berna, Y. Ren, *et al.*, Walking responses of Tribolium castaneum (Coleoptera: Tenebrionidae) to its aggregation pheromone and odors of wheat infestations, *J. Econ. Entomol.*, 2017, **110**(3), 1351–1358.

25 S. A. Trejo, S. Reinoso, W. A. VargasE. Abrahamovich, N. Pedrini, J. R. Girotti, *et al.*, Sexual attraction pheromone of tribolium castaneum and insect control device, *US Pat.*, US12171234B2, 2024.

26 R. R. Harman, W. R. Morrison III, A. Bruce, S. Ranabhat, H. E. Quellhorst, R. V. Wilkins, *et al.*, The behavioral response to the putative necromones from dead Tribolium castaneum (Coleoptera: Tenebrionidae) in traps by

conspecifics as a function of density and time since capture, *Environ. Entomol.*, 2023, **52**(6), 1020–1032.

27 C. G. Athanassiou, N. G. Kavallieratos and J. F. Campbell, Capture of Tribolium castaneum and Tribolium confusum (Coleoptera: Tenebrionidae) in floor traps: the effect of previous captures, *J. Econ. Entomol.*, 2016, **109**(1), 461–466.

28 S. A. Romero, J. F. Campbell, J. R. Nechols and K. A. With, Movement behavior of red flour beetle: response to habitat cues and patch boundaries, *Environ. Entomol.*, 2010, **39**(3), 919–929.

29 J. F. Campbell, M. D. Toews, F. H. Arthur and R. T. Arbogast, Long-term monitoring of Tribolium castaneum in two flour mills: seasonal patterns and impact of fumigation, *J. Econ. Entomol.*, 2010, **103**(3), 991–1001.

30 J. F. Campbell, M. D. Toews, F. H. Arthur and R. T. Arbogast, Long-term monitoring of Tribolium castaneum populations in two flour mills: rebound after fumigation, *J. Econ. Entomol.*, 2010, **103**(3), 1002–1011.

31 C. W. Doud, G. W. Cuperus, P. Kenkel, M. E. Payton and T. W. Phillips, Trapping Tribolium castaneum (Coleoptera: Tenebrionidae) and Other Beetles in Flourmills: Evaluating Fumigation Efficacy and Estimating Population Density, *Insects*, 2021, **12**(2), 144.

32 P. Barrer, A field demonstration of odour-based, host-food finding behaviour in several species of stored grain insects, *J. Stored Prod. Res.*, 1983, **19**(3), 105–110.

33 J. Campbell, Attraction of walking Tribolium castaneum adults to traps, *J. Stored Prod. Res.*, 2012, **51**, 11–22.

34 A. A. Semeao, J. F. Campbell, R. J. Whitworth and P. E. Sloderbeck, Response of Tribolium castaneum and Tribolium confusum adults to vertical black shapes and its potential to improve trap capture, *J. Stored Prod. Res.*, 2011, **47**(2), 88–94.

35 W. J. Bell, Searching behavior patterns in insects, *Annu. Rev. Entomol.*, 1990, **35**(1), 447–467.

36 K. A. Buckman and J. F. Campbell, How varying pest and trap densities affect T ribolium castaneum capture in pheromone traps, *Entomol. Exp. Appl.*, 2013, **146**(3), 404–412.

37 G. J. Daglish, A. W. Ridley, R. Reid and G. H. Walter, Testing the consistency of spatio-temporal patterns of flight activity in the stored grain beetles Tribolium castaneum (Herbst) and Rhyzopertha dominica (F.), *J. Stored Prod. Res.*, 2017, **72**, 68–74.

38 T. S. Rajan, V. Muralitharan, G. Daglish, S. Mohankumar, M. Rafter, S. Chandrasekaran, *et al.*, Flight of three major insect pests of stored grain in the monsoonal tropics of India, by latitude, season and habitat, *J. Stored Prod. Res.*, 2018, **76**, 43–50.

39 P. A. Sajeewani, D. M. Dissanayaka, L. K. Wijayaratne and C. S. Burks, Changes in Shape, Texture and Airflow Improve Efficiency of Monitoring Traps for Tribolium castaneum (Coleoptera: Tenebrionidae), *Insects*, 2020, **11**(11), 778.

40 A. Reza and S. Parween, Differential preference of colored surface in Tribolium castaneum (Herbst), *Invertebrate Surviv. J.*, 2006, **3**(2), 84–88.

41 M. D. Toews and C. Nansen, 21 Trapping and Interpreting Captures of Stored Grain Insects, *Stored Prod. Prot.*, 2012, 243.

42 R. T. Arbogast, P. E. Kendra, R. W. Mankin and J. E. McGovern, Monitoring insect pests in retail stores by trapping and spatial analysis, *J. Econ. Entomol.*, 2000, **93**(5), 1531–1542.

43 F. H. Arthur, L. A. Starkus, A. R. Gerken, J. F. Campbell and T. McKay, Growth and development of Tribolium castaneum (Herbst) on rice flour and brown rice as affected by time and temperature, *J. Stored Prod. Res.*, 2019, **83**, 73–77.

44 A. R. Gerken and W. R. Morrison III, Pest management in the postharvest agricultural supply chain under climate change, *Front. Agronomy*, 2022, **4**, 918845.

45 J. Campbell, M. Mullen and A. Dowdy, Monitoring stored-product pests in food processing plants with pheromone trapping, contour mapping, and mark-recapture, *J. Econ. Entomol.*, 2002, **95**(5), 1089–1101.

46 J. D. DeCoursey, A method of trapping the confused flour beetle, Tribolium confusum Duval, *J. Econ. Entomol.*, 1931, **24**(5), 1079–1081.

47 A. V. Barak and W. E. Burkholder, Trapping studies with dermestid sex pheromones, *Environ. Entomol.*, 1976, **5**(1), 111–114.

48 H. Williams, R. Silverstein, W. Burkholder and A. Khorramshahi, Dominicalure 1 and 2: components of aggregation pheromone from male lesser grain borer Rhyzopertha dominica (F.)(Coleoptera: Bostrichidae), *J. Chem. Ecol.*, 1981, **7**(4), 759–780.

49 T. Wyatt, J. Wynn and A. Phillips, The beetle is always right: using trap catch data and behavioural responses to design the ultimate stored product beetle trap, *Bull. SROP*, 1989, **12**(2), 94–95.

50 B. Lindgren, A multiple funnel trap for scolytid beetles (Coleoptera), *Can. Entomol.*, 1983, **115**(3), 299–302.

51 A. Barak and W. Burkholder, A versatile and effective trap for detecting and monitoring stored-product Coleoptera, *Agric., Ecosyst. Environ.*, 1985, **12**(3), 207–218.

52 M. A. Mullen, Development of a pheromone trap for monitoring Tribolium castaneum, *J. Stored Prod. Res.*, 1992, **28**(4), 245–249.

53 V. Stejskal, The influence of food and shelter on the efficacy of a commercial sticky trap in Tribolium castaneum (Coleoptera: Tenebrionidae), *J. Stored Prod. Res.*, 1995, **31**(3), 229–233.

54 P. Cogan and D. Hartley, *The Effective Monitoring of Stored Product Moths Using a Funnel Pheromone Trap*, 1984.

55 D. Dissanayaka, A. Sammani and L. Wijayaratne, Response of different population sizes to traps and effect of spinosad on the trap catch and progeny adult emergence in Tribolium castaneum (Herbst)(Coleoptera: Tenebrionidae), *J. Stored Prod. Res.*, 2020, **86**, 101576.

56 P. Agrafioti, E. Lampiri, E. Kaloudis, M. Gourgouta, T. N. Vassilakos, P. M. Ioannidis, *et al.*, Spatio-Temporal Distribution of Stored Product Insects in a Feed Mill in Greece, *Agronomy*, 2024, **14**(12), 2812.