Plant Archives Vol. 25, No. 1, 2025 pp. 1349-1364 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.v25.no.1.200

PHEROMONE TRAPS IN INSECT PEST MANAGEMENT: A COMPREHENSIVE REVIEW OF THEIR APPLICATIONS, EFFICACY AND FUTURE DIRECTIONS IN INTEGRATED PEST MANAGEMENT

Nagendra Kumar[1], Gudipati Naveen[2], Sudipta Padhan[3], Sanjay Hembram[4], Tanya Rathore[5], Smaranika Mohanta[6] and Arghya Mani[7]*

[1]Department of Entomology, PGCA, Dr. RPCAU, Pusa, Bihar, India.
[2]Department of Pesticide Management Division, National Institute of Plant Health Management, Hyderabad, Telangana, India.
[3]Department of Plant Protection (Entomology), Horticulture College, Khuntpani, Chaibasa, Birsa Agricultural University, Jharkhand, India.
[4]Birsa Agricultural University, Ranchi, India.
[5]Department of Plant Pathology), Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, U.P., India.
[6]Centurion University of Technology and Management, Odisha, India.
[7]Assistant Director of Horticulture, DFPI&H, Government of West Bengal, India.
*Corresponding author E-mail : manifruitpostharvest@gmail.com
(Date of Receiving-16-01-2025; Date of Acceptance-18-04-2025)

ABSTRACT

Pheromone-based pest management has emerged as a cornerstone of modern integrated pest management (IPM) systems, offering species-specific, ecologically benign alternatives to conventional chemical insecticides. This comprehensive review synthesizes the current state of research on pheromone traps, highlighting their biochemical foundation, technological evolution, field applications, and future prospects. The paper explores the intricate chemical communication mechanisms that underlie pheromone detection in insects, evaluates the diversity of dispenser systems and trap architectures, and discusses real-world deployment strategies in various cropping systems. Furthermore, this review critically assesses the economic viability, environmental benefits, operational challenges and emerging innovations, including the integration of pheromone traps with smart agriculture, nanotechnology and autonomous monitoring platforms. With more than 1,500 insect pheromones characterized and over 300 formulations commercially deployed, this field represents a dynamic and rapidly expanding frontier in sustainable crop protection.

Key words : Pheromone, Integrated Pest Management, Nanotechnology.

Introduction

Agricultural ecosystems worldwide are facing unprecedented challenges due to the increasing intensity and frequency of insect pest outbreaks, driven not only by the expansion of global trade but also by the impacts of climate change on pest biology and distribution (Pureswaran *et al.*, 2018). These pests can significantly compromise both the quantity and quality of crop production, posing a critical threat to global food security and rural economies (Deutsch *et al.*, 2018). Despite decades of advancement in chemical pesticide development, insect pest management continues to struggle with limitations related to pesticide resistance, non-target toxicity, ecological imbalance, and regulatory constraints on chemical residues in food and the environment (Sparks and Nauen, 2015).

The adoption of pheromone-based monitoring and management has steadily expanded over recent decades, as these tools offer several key advantages: they are species-specific, non-toxic to humans and beneficial organisms, compatible with other control methods, and help reduce unnecessary insecticide applications by enabling precision-based decision-making (Miller and Gut, 2015). Pheromone traps not only serve as early warning systems for the timely detection of pest population buildup but can also be used in mass trapping and mating disruption strategies, ultimately contributing to long-term pest population suppression (Cardé and Minks, 1995). The progressive refinement of synthetic pheromone identification, formulation, and dispenser technologies has led to the commercialization of more than 300 pheromone-based products, now widely used in both open-field agriculture and controlled environments (Minks and van der Kraan, 2005). Simultaneously, the integration of pheromone traps into precision agriculture systems — including remote sensing, automated pest counting, and real-time data transmission — marks a new frontier in sustainable pest management (Jaffe *et al.,* 2019).

This review aims to provide a comprehensive overview of pheromone trap technology, from the underlying chemical ecology and physiological mechanisms of pheromone perception to the practical applications, technological advances, and challenges involved in its implementation across diverse cropping systems. In doing so, it underscores the significant role of pheromone traps as a cornerstone of environmentally friendly pest management strategies and explores their potential to support global efforts toward reducing pesticide reliance and promoting agricultural sustainability (Brennan, 2016).

The discovery of insect pheromones, beginning with the isolation of bombykol in silkworm moths (Butenandt *et al*., 1959), laid the groundwork for a new era in pest management. Pheromones are highly specific, non-toxic signaling molecules that facilitate communication between conspecifics, particularly in mating, aggregation, and alarm signaling (Karlson and Lüscher, 1959). To date, over 1,500 insect pheromones have been identified (El-Sayed, 2023), with applications spanning monitoring, mass trapping, and mating disruption in commercial agriculture. Reflecting their increasing adoption, the global insect pheromone market was valued at $2.1 billion in 2022 and is expected to expand at a compound annual growth rate (CAGR) of 15.3% (Markets and Markets, 2023). This growth trajectory is fueled by rising demand for environmentally sustainable pest control methods that comply with stringent residue regulations and align with organic certification standards (Norin, 2007).

Biochemical Foundations : Insect communication is predominantly mediated by chemical signals, with pheromones serving as one of the most evolutionarily refined modes of intraspecific interaction (Wyatt, 2020). These semiochemicals are secreted and perceived with astonishing specificity, enabling insects to perform crucial survival functions such as mate finding, territory marking, aggregation, and alarm signaling in highly competitive and often ephemeral ecological niches (El-Sayed, 2023).

Pheromone chemistry

The chemical structures of insect pheromones are incredibly diverse, tailored through evolutionary pressures to ensure species-specific recognition even amidst overlapping habitats and coexisting related species (Tillman *et al*., 1999). The majority of insect pheromones fall into well-characterized classes, including:

Unsaturated Aliphatic hydrocarbons : Insect pheromones often feature unsaturated aliphatic hydrocarbons, typically between C10 and C18, as key structural motifs (Blomquist and Bagnères, 2010). The precise position and geometry (cis/trans or Z/E) of double bonds in these molecules are crucial for species specificity. Even slight changes in double-bond positioning can significantly impact biological activity, highlighting the intricate optimization of chemical signals in insect populations (Symonds and Elgar, 2008).

Oxygenated Derivatives : In addition to hydrocarbons, insects utilize oxygenated derivatives to refine pheromone properties. Functional groups like aldehydes, alcohols, acetates and esters modulate volatility, stability and receptor-binding affinity (Jurenka, 2004). Examples include (Z)-9-tricosenal in house flies (Carlson *et al*., 1971) and (E,E)-8,10-dodecadien-1-yl acetate in the European grapevine moth (Roelofs *et al*., 1973). These modifications enable insects to adapt their signals to specific environmental conditions, such as temperature and humidity, ensuring effective communication (Cardé and Millar, 2009).

Species-Specific Multi-component blends : In most cases, a single compound is insufficient to elicit a full behavioral response. Instead, insects rely on complex pheromone blends, where the relative ratios of components are finely optimized through natural selection. For example, the codling moth (*Cydia pomonella*) utilizes a 95:5 ratio of Z/E geometric isomers of codlemone ((E,E)-8,10-dodecadien-1-ol), a balance that must be matched precisely in synthetic lures to achieve field-level efficacy (Witzgall *et al*., 2010). In addition to their precision, insect pheromones are often produced in extremely low quantities, yet are biologically active at astonishingly low threshold levels, sometimes in the femtogram range. Even slight deviations in the enantiomeric purity or blend ratios can lead to either dramatically reduced attraction or behavioral antagonism (Löfstedt, 1993), illustrating the fine-tuned coevolution between signal emitters and receivers.

Perception mechanisms

The reception of pheromone signals in insects is a multi-layered process involving the detection, transport,

Table 1 : Pheromone Trap technologies, Dispenser type, Release rate and Field longevity.

Dispenser Type	Release Rate	Field Longevity	Typical Applications
Rubber Septa	0.1–10 mg/day	4–8 weeks	Codling moth (*Cydia pomonella*), tortricid species
Microcapsules	0.01–1 mg/day	8–12 weeks	Cotton bollworm (*Helicoverpa armigera*)
Membrane Dispensers	0.5–5 mg/day	10–16 weeks	Olive fruit fly (*Bactrocera oleae*)

and neural integration of chemical information, which ultimately results in a stereotyped behavioral response such as mate-seeking, oviposition site selection or aggregation.

Odorant-Binding Proteins (OBPs) : Since pheromones are typically hydrophobic, their solubilization and transport within the aqueous environment of the insect olfactory sensillum is facilitated by specialized carrier proteins known as odorant-binding proteins (OBPs). These proteins bind to pheromone molecules in the sensillar lymph, shielding them from degradation and delivering them directly to the surface of the olfactory receptor neurons (ORNs) for detection (Leal, 2013). Some OBPs even exhibit binding specificity for certain isomers or pheromone subtypes, further sharpening the selectivity of the detection system.

Chemosensory Receptors : Upon delivery to the neuronal membrane, pheromones interact with olfactory receptors (ORs), ionotropic receptors (IRs), or gustatory receptors (GRs). These receptors form part of highly sensitive molecular complexes capable of detecting pheromone concentrations in the sub-picogram range (Sato and Touhara, 2009). This hyper-sensitivity enables male insects, for example, to locate a mate from several hundred meters away under favorable conditions. In some species, the detection system even shows an extraordinary degree of neuronal wiring, where each glomerulus in the antennal lobe is tuned to a particular component or ratio of the pheromone blend (Hansson and Anton, 2000). This system enables the insect to filter background odors and respond with near-instantaneous behavioral precision.

Central Nervous System Integration : Once detected, the pheromone signal is relayed via action potentials to the insect brain, specifically the antennal lobes — a structure analogous to the olfactory bulb in vertebrates. Here, the signals are processed in a spatially organized manner by glomeruli, which act as discrete "pheromone filters" (Galizia and Rössler, 2010). Subsequent higher-order processing in the mushroom bodies and lateral protocerebrum allows insects to integrate pheromonal cues with environmental information such as wind direction, visual stimuli, and previous experience, enabling adaptive behavioral responses. This tightly regulated detection and signal transduction pathway underscores the evolutionary importance of pheromonal communication in insect survival and reproduction. The deep understanding of these mechanisms not only enhances the design of pheromone lures and dispensers but also opens new frontiers in disrupting pest behavior for agricultural benefit.

Pheromone Trap Technologies

The success of pheromone-based pest management systems hinges not only on the accurate chemical mimicry of natural pheromones, but also on the physical means by which these semiochemicals are delivered and dispersed into the environment. The design of dispensers and traps plays a crucial role in ensuring optimal field performance, cost-effectiveness and ease of deployment across diverse agroecosystems. Advancements in materials science and behavioral ecology have together driven significant innovations in both dispenser formulations and trap architectures.

Dispenser Systems : A key component of any pheromone-based control strategy is the dispenser, which is responsible for releasing the active compound(s) into the environment at biologically relevant concentrations over a prolonged period. The ideal dispenser should achieve a controlled and predictable release rate, withstand variable climatic conditions (particularly UV radiation and rainfall), and minimize labor costs by reducing the frequency of replacement.

Rubber septa are among the most widely used dispensers due to their affordability, ease of handling, and suitability for both monitoring and mass trapping. However, their release profiles can be influenced by temperature and wind conditions, which occasionally require compensation by adjusting the dispenser load or replacement frequency.

Microencapsulated formulations have emerged as an attractive alternative for field applications that demand extended longevity and uniform pheromone release. These formulations typically consist of pheromone molecules encapsulated within biodegradable polymer shells, which release the active compound through diffusion and surface erosion. Microencapsulation also offers the advantage of reduced photodegradation and compatibility with sprayable delivery systems (Campos *et al*., 2021).

Membrane dispensers are engineered using synthetic polymers designed to maintain a constant release rate over extended periods. Their application is especially advantageous in large-scale mating disruption programs where uniform coverage and minimal servicing are required (Mazomenos *et al*., 2002). These dispensers also exhibit improved resistance to weather-induced fluctuations in release rates compared to older septa-based systems.

Recent advancements have also explored the integration of nanotechnology-based delivery systems, including nanoparticle encapsulation, dendrimers and liposomal formulations. These approaches offer improved pheromone stability, reduced oxidation, and the potential for smart release profiles responsive to environmental triggers such as humidity or light intensity (Benelli *et al*., 2020). Additionally, biodegradable polymer matrices are being developed to enhance environmental safety and reduce plastic waste in large-scale pheromone deployment campaigns (Kumar *et al*., 2022).

Trap designs

The physical structure of pheromone traps is another decisive factor influencing pest capture efficiency, especially in the context of varying pest behaviors (e.g., flight patterns, visual attraction) and microclimatic conditions (e.g., wind direction, humidity). Trap designs are typically species-specific and often adapted for different operational goals such as monitoring, mass trapping, or behavioral studies.

Delta Traps : Widely used for the monitoring of Lepidopteran pests, delta traps consist of a triangular prism-shaped body fitted with an adhesive liner and a lure-holding position. Their simplicity, reusability and ease of pheromone bait replacement make them ideal for routine field surveillance, especially in orchards and vineyards.

Funnel Traps : Designed for pests with active flight and strong attraction to vertical visual cues, funnel traps are typically used for bark beetles (Scolytinae) and weevils (Curculionidae). These traps feature a series of interlocking funnels or vanes that guide the insect into a collection chamber, often fitted with an insecticidal strip or a drowning fluid to prevent escape.

Bucket Traps : Particularly effective for fruit flies (Diptera: Tephritidae), bucket traps employ a pheromone or food-based attractant suspended above an insecticide-treated chamber. These traps offer high insect-holding capacity and are suited for both monitoring and suppression of adult populations in orchard and horticultural systems.

Sticky Traps : One of the most economical and versatile designs, sticky traps are coated with adhesive material and baited with a pheromone lure. Though highly effective in early detection and density estimation, their adhesive surfaces are prone to saturation in high-infestation scenarios and require regular maintenance and replacement.

Emerging trap designs increasingly integrate visual and olfactory multimodal cues, including UV-reflective surfaces, color contrasts and secondary attractants such as kairomones or food baits, to enhance species-specific capture rates and reduce non-target bycatch (Reddy and Guerrero, 2004). Hybrid traps combining pheromone lures with automated electronic monitoring systems (such as optical sensors, camera traps, or smart counters) are also becoming increasingly common, particularly in precision agriculture frameworks (Potamitis *et al*., 2017).

Practical applications of pheromone in cultivation : Pheromone traps have become indispensable tools in the management of insect pests in high-value horticultural systems, where tolerance for cosmetic damage and chemical residues is particularly low. The following case studies illustrate the diversity and success of pheromone-based strategies in fruit and orchard crops:

Pest management in Orchards and Fruit Crops

Codling moth (*Cydia pomonella*) — Apple, Pear, Walnut : As one of the most studied pests in pheromone-based management, codling moth control using mating disruption and trap-based monitoring has led to a 50–75% reduction in insecticide use in apple orchards globally. Area-wide programs in Europe and North America have also significantly delayed the development of insecticide resistance (Witzgall *et al*., 2008).

Oriental Fruit Moth (*Grapholita molesta*) — Peach, Nectarine, Plum : In stone fruit orchards, pheromone-baited delta traps are widely used to track moth population fluctuations. Mating disruption with pheromone dispensers has cut infestation rates by up to 90% and reduced pesticide inputs by more than 50% in European integrated fruit production systems (Ioriatti *et al*., 2011).

Mediterranean Fruit Fly (*Ceratitis capitata*) — Citrus, Peach, Plum, Apricot : Mass trapping with parapheromone lures like trimedlure and methyl eugenol, combined with insecticide-bait stations, has significantly reduced population density and fruit infestation levels, especially in Spanish citrus orchards (Navarro-Llopis *et al*., 2008).

European Grapevine Moth (*Lobesia botrana*) — Grapes : Mating disruption techniques using pheromone dispensers have led to dramatic reductions in insecticide use and improved bunch quality in viticultural regions across Italy, Austria, Spain, and France (Ioriatti *et al*., 2011).

Apple Clearwing Moth (*Synanthedon myopaeformis*) — Apple : Pheromone-based monitoring has enabled early detection of this wood-boring pest, improving the timing of control measures and reducing tree damage in European orchards (Witzgall *et al*., 2001).

Guava Fruit fly (*Bactrocera correcta*) — Guava : Pheromone traps baited with methyl eugenol have proven highly effective in monitoring and reducing fruit fly populations in guava plantations across South and Southeast Asia, contributing to a substantial reduction in fruit damage and pesticide applications (Ekesi *et al*., 2006).

Olive Fruit fly (*Bactrocera oleae*) — Olive: Pheromone-baited McPhail and yellow sticky traps are commonly used to monitor adult fly emergence, allowing precision timing for insecticidal bait sprays and significantly improving olive oil quality by minimizing infestation levels (Navarro-Llopis *et al*., 2011).

Cherry Fruit fly (*Rhagoletis cerasi*) — Sweet Cherry : Sticky yellow panel traps combined with ammonium carbonate as a food lure or pheromone blends have improved the early detection and control of this pest in European cherry orchards, reducing pesticide residue concerns for export markets (Daniel and Baker, 2013).

Persimmon Fruit Moth (*Stathmopoda masinissa*) — Persimmon : Pheromone-baited traps enable effective monitoring of adult moth activity in Japanese persimmon orchards, allowing the implementation of targeted interventions during peak oviposition periods (Kishimoto *et al*., 2008).

Peach Twig Borer (*Anarsia lineatella*) — Peach, Apricot, Nectarine : Pheromone traps are widely used for both monitoring and mating disruption, significantly lowering larval damage to twigs and fruits while reducing reliance on broad-spectrum insecticides (Knight *et al*., 2014).

Pest management in Field crops

Pink Bollworm (*Pectinophora gossypiella*) — Cotton : Pheromone-baited traps have been successfully employed for both monitoring and mass trapping of *P. gossypiella*, a key pest in cotton worldwide. Field implementation of pheromone-based strategies has led to substantial reductions in insecticide use and contributed to the eradication of pink bollworm in some U.S. cotton-producing regions (Tabashnik *et al*., 2010).

Sugarcane Shoot Borer (*Chilo infuscatellus*) — Sugarcane : Sex pheromone traps help track adult moth emergence and peak flight activity, allowing farmers to apply control measures precisely during the egg-laying window, which significantly improves pest management outcomes and reduces chemical overuse (Sharma and Varma, 1993).

Yellow Stem Borer (*Scirpophaga incertulas*) — Rice : Pheromone trap-based monitoring programs in rice paddies have been instrumental in improving spray schedules, reducing unnecessary pesticide usage, and lowering production costs while preserving beneficial insect populations (Katti *et al*., 2001).

Sesame Leaf Webber (*Antigastra catalaunalis*) — Sesame : Pheromone lures have been used to detect and monitor *A. catalaunalis* in sesame fields, allowing for timely mechanical and chemical interventions that significantly reduced crop losses, especially under rainfed conditions (Patil and Vyakarnahal, 2001).

Groundnut Leaf miner (*Aproaerema modicella*) — Groundnut (Peanut) : Pheromone traps serve as a reliable method for population monitoring, enabling more precise pesticide applications and integrated pest management practices that reduce environmental and economic costs (Wightman and Ranga Rao, 1993).

Stem Borer Complex (*Chilo partellus, Sesamia inferens*) — Maize, Sorghum : In cereal systems, pheromone traps have improved early pest detection, enabling timely biopesticide and parasitoid release as part of integrated pest management, resulting in yield preservation and reduced insecticide dependence (Kfir *et al*., 2002).

Soybean Looper (*Chrysodeixis includens*) — Soybean : In Brazil and Argentina, pheromone monitoring traps have been integrated into large-scale soybean pest management programs, enabling early detection and precise insecticide use, cutting costs and lowering ecological impact.

Sugarcane Shoot Borer (*Chilo infuscatellus*) : Pheromone traps in Indian and Southeast Asian sugarcane fields provide an early-warning system for borer outbreaks, enabling farmers to adopt stage-specific pest management strategies, including parasitoid releases and selective insecticides (Padinjaremadathil *et al*., 2016).

Pest management in Agriculture commodity

during storage : Pheromone traps are instrumental in managing pest infestations in stored grains and processed products. Their ability to detect early infestations before visible damage occurs allows for timely intervention, reducing the reliance on chemical fumigants and improving the overall quality and safety of stored products.

Indianmeal Moth (*Plodia interpunctella*) — Grains, Dried Fruits, Nuts : Pheromone traps have become a standard tool in grain storage facilities, effectively detecting *P. interpunctella* infestations 2–3 weeks before visible signs of damage. Early intervention based on trap data has significantly reduced product loss, particularly in grain mills and food processing plants (Trematerra, 2012).

Khapra Beetle (*Trogoderma granarium*) — Wheat, Rice, Barley, Pulses : This quarantine pest is closely monitored using aggregation pheromones, which help improve the detection of *T. granarium* in grain shipments. These traps are particularly effective in detecting low-level infestations, which is crucial for preventing the spread of this highly regulated pest in international trade (Hagstrum and Subramanyam, 2009).

Grain Weevils (*Sitophilus* spp.) — Stored Grains (Wheat, Rice, Corn) : Pheromone traps for *Sitophilus* species have been widely used in grain storage to detect and monitor weevil populations. These traps help inform the timing of fumigation treatments and contribute to reduced pesticide use by offering early warning signs of infestation (Subramanyam and Hagstrum, 2000).

Cigarette Beetle (*Lasioderma serricorne*) — Tobacco, Dried Spices, Herbs : Cigarette beetles infest stored tobacco, dried herbs, and spices. Pheromone traps are used to monitor adult populations, allowing for the early application of control methods such as heat treatment or low-level fumigation, which significantly reduces the need for broad-spectrum chemical pesticides (Stathas *et al*., 2012).

Rusty Grain Beetle (*Cryptolestes ferrugineus*) — Grains, Flour : This pest is a common problem in flour mills and grain storage facilities. Pheromone traps have been shown to effectively monitor beetle populations, leading to more targeted treatments and reducing product contamination. Their use has helped grain storage facilities minimize infestations and prevent the spread of *C. ferrugineus* in stored products (Hagstrum *et al*., 2015).

Sawtoothed Grain Beetle (*Oryzaephilus surinamensis*) — Stored Grains, Cereal products : Using sex pheromone-based traps has allowed early detection of *O. surinamensis*, a widespread pest in stored cereals. These traps have helped identify the presence of pests long before visible damage occurs, allowing for more efficient and effective pest management strategies (Scholtz and Schöller, 2018).

Pest management in Vegetable crops : In vegetable production systems, pest pressure is often intense due to continuous cultivation cycles, high plant density, and the vulnerability of tender plant tissues to damage. Pheromone-based pest monitoring and control methods have shown promising results across a wide variety of vegetable crops.

Tomato Fruit Borer (*Helicoverpa armigera*) — Tomato, Bell Pepper, Eggplant : Pheromone traps, typically delta or funnel types, have proven highly effective in early detection and population monitoring. Their use has allowed more targeted insecticide application, reducing chemical inputs by 30–50% while preventing fruit losses in both open-field and greenhouse tomato systems (Cork *et al*., 2005).

Diamond back Moth (*Plutella xylostella*) — Cabbage, Cauliflower, Broccoli : Pheromone traps play a vital role in integrated pest management for cruciferous crops, enabling precise forecasting of peak moth flights and significantly reducing unnecessary insecticide sprays. Field studies report up to a 40% reduction in pesticide applications when trap thresholds guide control decisions (Furlong *et al*., 2013).

Melon Fly (*Bactrocera cucurbitae*) — Cucumber, Bitter Gourd, Pumpkin, Squash, Melon : Methyl eugenol and cue-lure baited traps have been successfully deployed in melon and cucurbit crops for both mass trapping and early infestation warning. Combined with field sanitation, this strategy has reduced fruit damage by more than 60% (Vargas *et al*., 2010).

Brinjal Fruit and Shoot Borer (*Leucinodes orbonalis*) — Eggplant : Sex pheromone traps for *L. orbonalis* are highly effective for population monitoring and mass trapping. When integrated with cultural control methods, pheromone trap deployment has resulted in yield increases of 20–30% by reducing fruit borer infestation levels (Srinivasan, 2008).

Legume Pod Borer (*Maruca vitrata*) — Cowpea, Yardlong Bean, Pigeon Pea : Pheromone traps enable accurate monitoring of this destructive pest in legume crops, particularly in tropical and subtropical regions. Early detection through trap-based surveillance has helped synchronize targeted biopesticide applications, improving control efficacy and reducing damage by over 50% in some cases (Shylesha *et al*., 2006).

***Spodoptera litura* — Leafy Vegetables and Solanaceous crops :** Pheromone-baited bucket traps and water traps are used to monitor the adult moth populations of *S. litura* in crops like spinach, amaranth, tomato, and chili. Trap-based monitoring helps reduce excessive insecticide spraying and has improved the economic threshold-based decision-making framework for pest management (Dhir *et al.*, 2020).

Pest management in Plantation and Industrial Crops

Coffee Berry Borer (*Hypothenemus hampei*): In coffee plantations worldwide, pheromone-baited funnel traps are employed to monitor adult population dynamics. Trapping data helps optimize harvest timing and insecticide applications, lowering both pesticide residues and economic loss (Dufour *et al.*, 2002).

Table 2 : Pest management in Orchards and Fruit crops using pheromone technology.

S. no.	Crop/Pest	Target crop(s)	Pheromone Management Technique	Impact and Results	Citations
01	**Codling Moth (*Cydia pomonella*)**	Apple, Pear, Walnut	Mating disruption, trap-based monitoring	50–75% reduction in insecticide use; delayed insecticide resistance development	Witzgall *et al.* (2008)
02	**Oriental Fruit Moth (*Grapholita molesta*)**	Peach, Nectarine, Plum	Pheromone-baited delta traps, mating disruption	90% infestation reduction; 50% reduction in pesticide use	Ioriatti *et al.* (2011)
03	**Mediterranean fruit fly (*Ceratitis capitata*)**	Citrus, Peach, Plum, Apricot	Mass trapping with parapheromone lures (trimedlure, methyl eugenol), insecticide-bait stations	Significant reduction in population density and fruit infestation, particularly in Spanish citrus orchards	Navarro-Llopis *et al.* (2008)
04	**European Grapevine Moth (*Lobesia botrana*)**	Grapes	Mating disruption with pheromone dispensers	Reduction in insecticide use and improved bunch quality across Italy, Austria, Spain, and France	Ioriatti *et al.* (2011)
05	**Apple Clearwing moth (*Synanthedon myopaeformis*)**	Apple	Pheromone-based monitoring	Early detection and reduced tree damage in European orchards	Witzgall *et al.* (2001)
06	**Guava Fruit fly (*Bactrocera correcta*)**	Guava	Pheromone traps baited with methyl eugenol	Effective monitoring and reduction of fruit fly populations in South and Southeast Asia, with reduced pesticide applications	Ekesi *et al.* (2006)
07	**Olive Fruit fly (*Bactrocera oleae*)**	Olive	Pheromone-baited McPhail and yellow sticky traps	Improved timing for insecticide applications, reduced infestation levels, and enhanced olive oil quality	Navarro-Llopis *et al.* (2011)
08	**Cherry Fruit fly (*Rhagoletis cerasi*)**	Sweet Cherry	Sticky yellow panel traps with ammonium carbonate or pheromone blends	Early detection and control, reduced pesticide residue for export markets	Daniel and Baker (2013)
09	**Persimmon Fruit moth (*Stathmopoda masinissa*)**	Persimmon	Pheromone-baited traps	Effective monitoring and intervention during peak oviposition periods in Japanese persimmon orchards	Kishimoto *et al.* (2008)
10	**Peach Twig borer (*Anarsia lineatella*)**	Peach, Apricot, Nectarine	Pheromone traps for monitoring and mating disruption	Reduced twig and fruit damage, lower pesticide reliance	Knight *et al.* (2014)

Table 3 : Pest management in Vegetable crops using pheromone technology.

S. no.	Crop/Pest	Target crop(s)	Pheromone Management Technique	Impact and Results	Citations
01	**Tomato Fruit borer (*Helicoverpa armigera*)**	Tomato, Bell Pepper, Eggplant	Pheromone traps (delta or funnel types) for population monitoring	30-50% reduction in pesticide use, preventing fruit loss in open-field and greenhouse systems	Cork *et al*. (2005)
02	**Diamondback moth (*Plutella xylostella*)**	Cabbage, Cauliflower, Broccoli	Pheromone traps for moth flight prediction	40% reduction in pesticide applications	Furlong *et al*. (2013)
03	**Melon Fly (*Bactrocera cucurbitae*)**	Cucumber, Bitter Gourd, Pumpkin, Squash, Melon	Pheromone traps baited with methyl eugenol and cue-lure	60% reduction in fruit damage	Vargas *et al*. (2010)
04	**Brinjal Fruit and shoot borer (*Leucinodes orbonalis*)**	Eggplant	Pheromone traps for monitoring and mass trapping	20-30% increase in yield, reduced fruit borer infestation	Srinivasan (2008)
05	**Legume Pod borer (*Maruca vitrata*)**	Cowpea, Yardlong Bean, Pigeon Pea	Pheromone traps for monitoring and early detection	50% reduction in damage through synchronized biopesticide applications	Shylesha *et al*. (2006)
06	***Spodoptera litura***	Leafy vegetables, Solanaceous crops	Pheromone-baited bucket and water traps for population monitoring	Reduced insecticide spraying, improved pest management decision-making	Dhir *et al*., 2020

Bark Beetles (*Ips typographus*, *Dendroctonus* spp.) : In conifer forests across Europe and North America, aggregation pheromone traps have been deployed as both monitoring and control tools, enabling forest managers to identify outbreak hotspots and implement sanitation logging before large-scale tree mortality occurs (Fettig *et al*., 2007).

Palm Weevils (*Rhynchophorus ferrugineus*) — Date Palm and Coconut : Pheromone-baited traps combined with kairomone lures (*e.g.*, ethyl acetate) have become the cornerstone of early detection programs in the Middle East, North Africa and Southeast Asia, enabling timely removal of infested palms and avoiding catastrophic losses (Hallett *et al*., 2004).

Technological Innovations in pheromone trap based pest management : The role of technological innovations in the evolution of pheromone traps and pest management is indispensable. With rapid advancements in technology, the management of insect pests through pheromones has become more efficient, cost-effective, and environmentally friendly. The following sections highlight some key developments in this area.

Smart Monitoring Systems

Technological integration in pest management has revolutionized how pheromone traps operate. The advancements in sensor technologies, wireless communication, and artificial intelligence have elevated pest monitoring systems to unprecedented levels of efficiency.

Electronic Noses for Real-time Pheromone Detection : Electronic noses (e-noses) are a pioneering advancement in pest monitoring. These devices, capable of real-time detection of pheromone molecules, are being integrated into comprehensive pest monitoring networks. This integration allows for continuous data acquisition, improving the precision and reliability of pest detection (Röck *et al*., 2008). E-noses can identify specific pheromone profiles emitted by different pest species, providing early detection and enhancing pest control strategies. Furthermore, they can automatically send alerts to growers, enabling them to take timely action, such as deploying additional traps or initiating pest control measures.

Table 4 : Pest management in field crops using pheromone technology.

S. no.	Crop/Pest	Target crop(s)	Pheromone Management Technique	Impact and Results	Citations
01	**Pink Bollworm (*Pectinophora gossypiella*)**	Cotton	Pheromone-baited traps for monitoring and mass trapping	Reduced insecticide use and pink bollworm eradication in U.S. cotton regions	Tabashnik *et al.* (2010)
02	**Sugarcane Shoot borer (*Chilo infuscatellus*)**	Sugarcane	Pheromone traps for adult moth tracking	Improved pest management outcomes and reduced chemical use	Sharma and Varma (1993)
03	**Yellow Stem borer (*Scirpophaga incertulas*)**	Rice	Pheromone trap-based monitoring	Reduced pesticide use and production costs, preserved beneficial insects	Katti *et al.* (2001)
04	**Sesame Leaf webber (*Antigastra catalaunalis*)**	Sesame	Pheromone lures for detection and monitoring	Reduced crop losses and improved pest control under rainfed conditions	Patil and Vyakarnahal (2001)
05	**Groundnut Leaf miner (*Aproaerema modicella*)**	Groundnut (Peanut)	Pheromone traps for population monitoring	More precise pesticide applications, reduced environmental and economic costs	Wightman and Ranga Rao (1993)
06	**Stem Borer complex (*Chilo partellus, Sesamia inferens*)**	Maize, sorghum	Pheromone traps for early pest detection	Timely biopesticide and parasitoid releases, reduced insecticide use, and yield preservation	Kfir *et al.* (2002)
07	**Soybean Looper (*Chrysodeixis includens*)**	Soybean	Pheromone monitoring traps for early detection	Early detection, precise insecticide use and reduced ecological impact	Wightman and Ranga Rao (1993)
08	**Indianmeal moth (*Plodia interpunctella*)**	Grains, Dried Fruits, Nuts	Pheromone traps for early detection	Reduced product loss in grain mills and food processing plants by detecting infestations 2-3 weeks before visible damage	Trematerra (2012)
09	**Khapra beetle (*Trogoderma granarium*)**	Wheat, Rice, Barley, Pulses	Aggregation pheromones for detection	Improved detection of low-level infestations, crucial for preventing pest spread in international trade	Hagstrum and Subramanyam (2009)
10	**Sugarcane Shoot Borer (*Chilo infuscatellus*)**	Sugarcane	Pheromone traps for early warning	Stage-specific pest management strategies, reduced chemical use	Padinjaremadathil *et al.* (2016)

Internet of Things (IoT)-Enabled Traps: The advent of IoT technology has drastically improved pest monitoring by making data transmission more seamless. IoT-enabled traps can wirelessly transmit real-time insect count data to a centralized system, which displays the information on user-friendly dashboards. Growers can monitor pest pressure and detect pest outbreaks remotely, gaining valuable insights into pest populations. The data gathered is analyzed for trends and action thresholds, assisting in decision-making about pest control interventions (Potamitis *et al*., 2017). The integration of IoT allows farmers to optimize pesticide use and reduce overall reliance on chemical treatments, resulting in environmentally sustainable practices.

Drone-Assisted Deployment of Pheromone Dispensers : Drones are playing a crucial role in enhancing the precision and accessibility of pheromone dispenser deployment. Particularly in large or difficult-to-access agricultural areas, drones can deploy pheromone dispensers with high accuracy. This technology reduces the need for manual labor and makes it easier to target specific pest populations, even in remote

Table 5 : Pest management in Plantation and Industrial Crops using pheromone technology.

S. no.	Crop/Pest	Target crop(s)	Pheromone Management Technique	Impact and Results	Citations
01	**Coffee Berry borer (*Hypothenemus hampei*)**	Coffee	Pheromone-baited funnel traps	Optimized harvest timing, reduced pesticide residues and economic losses	Dufour *et al*. (2002)
02	**Bark Beetles (*Ips typographus*, *Dendroctonus* spp.)**	Conifer forests	Aggregation pheromone traps for monitoring and control	Early detection of outbreak hotspots, prevention of large-scale tree mortality	Fettig *et al*. (2007)
03	**Palm weevils (*Rhynchophorus ferrugineus*)**	Date Palm, Coconut	Pheromone traps with kairomone lures (ethyl acetate)	Early detection and removal of infested palms, preventing catastrophic losses	Hallett *et al*. (2004)

Table 6 : Pest management of crops during storage using pheromone technology.

S. no.	Crop/Pest	Target crop(s)	Pheromone Management Technique	Impact and Results	Citations
01	**Grain Weevils (*Sitophilus* spp.)**	Stored Grains (Wheat, Rice, Corn)	Pheromone traps for monitoring	Early detection of infestations, improved timing for fumigation treatments, and reduced pesticide use	Subramanyam and Hagstrum (2000)
02	**Cigarette beetle (*Lasioderma serricorne*)**	Tobacco, Dried Spices, Herbs	Pheromone traps for monitoring and early control	Early intervention with heat treatment or low-level fumigation, reducing broad-spectrum chemical pesticide use	Stathas *et al*. (2012)
03	**Rusty Grain beetle (*Cryptolestes ferrugineus*)**	Grains, flour	Pheromone traps for population monitoring	Targeted treatments and reduced infestation, leading to minimized contamination in grain storage facilities	Hagstrum *et al*. (2015)
04	**Sawtoothed Grain beetle (*Oryzaephilus surinamensis*)**	Stored Grains, Cereal Products	Sex pheromone-based traps for early detection	Early detection of infestations, improved pest management strategies	Scholtz and Schöller (2018)

or hazardous environments (Zhang *et al*., 2021). Drone-assisted pheromone deployment can improve pest control efficiency by ensuring that pheromone dispersal is uniform and reaches areas where traditional methods may be ineffective. Moreover, drones can cover vast areas in a shorter time, thereby improving response times during pest outbreaks.

Formulation advances

Innovative formulation technologies have further optimized the application and effectiveness of pheromone-based pest control methods. These advancements focus on improving the stability, release mechanisms, and environmental compatibility of pheromone products.

Nanocarriers for enhanced Pheromone Stability and Controlled release : The use of nanocarriers, such as liposomes and dendrimers, has greatly enhanced the performance of pheromone formulations. These nanomaterials offer improved stability for pheromones, protecting them from environmental degradation caused by factors like temperature, UV radiation, or humidity (Benelli *et al*., 2020). In addition, nanocarriers enable controlled-release mechanisms, allowing for the sustained release of pheromones over extended periods. This controlled release minimizes the need for frequent reapplication, which not only reduces labor costs but also provides long-lasting pest control. Furthermore, nanocarriers improve the targeting of pheromones, ensuring that they are delivered precisely where they are needed for optimal effectiveness.

Biodegradable Polymers in Pheromone Dispensers : As the world moves toward more sustainable practices, the use of biodegradable polymers in the manufacture of pheromone dispensers is gaining traction. These polymers are designed to break down naturally in the environment, reducing the risk of plastic contamination (Kumar *et al*., 2022). Their use aligns with the goals of the circular economy by minimizing waste and supporting the development of environmentally friendly pest management solutions. Additionally, biodegradable dispensers contribute to the reduction of microplastic pollution, which is a growing concern in agricultural systems. The transition to biodegradable materials enhances the ecological sustainability of pheromone-based pest control.

Multimodal Lures for Enhanced Attraction : The development of multimodal lures that combine pheromones with other semiochemicals, such as plant volatiles or kairomones, has significantly enhanced pest attraction and capture efficiency. These lures, which mimic the complex chemical signals that pests encounter in their natural environment, provide a more effective means of drawing pests into traps. This multimodal approach is particularly useful for polyphagous pests, which may be attracted to a range of different plant species. Combining pheromones with kairomones or plant volatiles creates a synergistic effect that enhances the lure's effectiveness, improving pest control and reducing the reliance on multiple types of pest management strategies (Reddy and Guerrero, 2004). Such lures offer a more holistic approach to pest management, targeting a wider range of pest behaviors.

Economic and Ecological Impacts of Pheromone-Based Pest Management in India: The integration of pheromone-based pest management (IPM) strategies in Indian agriculture is increasingly recognized for its substantial economic and ecological benefits. By reducing dependency on chemical pesticides and enhancing pest control efficiency, these strategies offer farmers a cost-effective, environmentally sustainable solution. Below is an analysis of the economic feasibility and biodiversity benefits of pheromone-based IPM in the Indian context.

Cost-Benefit analysis

The economic viability of pheromone-based pest management varies across different crops, with farmers reaping significant returns on their initial investment. This cost-benefit analysis presents the financial benefits of implementing pheromone-based IPM across various Indian crops, highlighting the return on investment (ROI) for each.

For instance, grapes offer the highest ROI at 4.1:1, with an initial cost of ` 14,500 per hectare, making pheromone-based pest management highly profitable for Indian grape growers. Similarly, mangoes show an impressive ROI of 3.5:1, with a cost of ` 16,000 per hectare. Apples and cotton follow closely with ROIs of 3.2:1 and 3.0:1, respectively. Even staple crops such as rice and wheat, with lower initial costs of ¹ 9,000 and ¹ 8,500 per hectare, show solid returns of 2.7:1 and 2.5:1, respectively. This demonstrates that pheromone-based IPM is financially advantageous for a wide range of Indian crops.

Additionally, the economic benefits are further enhanced when pheromone-based pest management is integrated with other pest control strategies, such as biological control, light traps and cultural practices. These integrated approaches reduce the need for chemical pesticides, lowering input costs and increasing long-term sustainability. By optimizing resources, these methods help farmers achieve better yields, reduce environmental impact, and improve overall farm profitability.

Biodiversity Benefits

Apart from economic advantages, pheromone-based pest management offers significant ecological benefits, particularly in the conservation of biodiversity. India, with

Table 7 : Initial Cost per ha and Return on Investment (ROI) on use of pheromone traps.

S. no.	Crop	Initial Cost per ha (INR)	Return on Investment (ROI)	Reference
01.	Apples	` 18,500	3.2:1	Mangan *et al*. (2006)
02.	Grapes	` 14,500	4.1:1	Lucchi *et al*. (2018)
03.	Rice	` 9,000	2.7:1	Cork *et al*. (2005)
04.	Cotton	` 10,500	3.0:1	Araujo *et al*. (2013)
05.	Wheat	` 8,500	2.5:1	Sharma *et al*. (2015)
06.	Mango	` 16,000	3.5:1	Reddy *et al*. (2012)
07.	Tomatoes	` 12,000	3.3:1	Chaudhary *et al*. (2016)
08.	Peanuts	` 7,500	2.9:1	Kumar *et al*. (2017)
09.	Soybean	` 10,000	2.8:1	Gupta *et al*. (2019)
10.	Sugarcane	` 13,000	2.9:1	Singh *et al*. (2014)

its rich biodiversity and diverse agricultural ecosystems, stands to benefit greatly from the adoption of such environmentally friendly pest management practices.

Reduction in Non-Target Organism Mortality: One of the most significant ecological advantages of pheromone-based IPM is the reduction in harm to non-target organisms. Research has shown that pheromone traps result in an 89% reduction in non-target organism mortality compared to conventional insecticides (Jactel *et al*., 2019). This is crucial in India, where beneficial insects such as pollinators, soil organisms, and natural pest predators play a vital role in maintaining ecosystem health. By protecting these essential species, pheromone-based systems contribute to the long-term resilience of Indian ecosystems.

Conservation of Natural Predators and Parasitoids : Pheromone-based pest management strategies help conserve predators and parasitoids, which are natural enemies of pests. These beneficial organisms are critical for regulating pest populations in Indian agricultural systems. The use of pheromones promotes the survival and effectiveness of these natural control agents, enhancing the overall pest management system. Studies have demonstrated that pheromone strategies foster the conservation of these species, contributing to natural biological control services and improving ecosystem resilience (Mills *et al*., 2016).

By maintaining a healthy balance between pests and their natural predators, pheromone-based systems ensure sustainable pest control, reducing the need for chemical pesticides. This not only protects biodiversity but also improves agricultural productivity by enhancing pollination, pest regulation, and soil fertility.

Limitations and solutions

Despite the promising economic and ecological benefits of pheromone-based pest management, several limitations continue to challenge its widespread adoption and operational efficiency. Both technical and social factors influence the overall success of these strategies. However, ongoing research and innovation are actively addressing these barriers, leading to the continuous refinement of pheromone-based integrated pest management (IPM) systems.

Technical Challenges

While pheromone-based technologies have revolutionized pest detection and control, they are not without technical limitations, particularly under real-world field conditions.

Environmental Degradation of Pheromone Lures : Pheromone compounds are inherently sensitive to environmental stressors, especially ultraviolet (UV) radiation and oxidation. Prolonged exposure to direct sunlight can degrade the active ingredients in lures, substantially reducing their efficacy and lifespan. This problem is particularly pronounced in tropical and subtropical regions like India, where high solar intensity accelerates lure degradation.

To mitigate this, recent advances in formulation chemistry have led to the development of pheromone lures embedded with UV stabilizers and antioxidants, which protect the active ingredients from premature breakdown, thereby enhancing field longevity and reducing the frequency of lure replacement.

Trap Saturation during High Pest Densities: In situations where pest populations are exceptionally high, pheromone traps can become saturated with captured insects in a short period. This compromises both the monitoring accuracy and the control effectiveness of the strategy, as saturated traps can no longer attract or capture additional pests, potentially leading to underestimations of pest pressure.

Modern solutions to this issue include the deployment of automated trap-emptying systems and the use of adaptive deployment densities — where trap density is dynamically adjusted based on real-time pest population data. These strategies ensure that traps maintain optimal performance even during peak infestation periods.

Adoption Barriers

Apart from technical issues, socioeconomic and institutional factors have also limited the widespread adoption of pheromone-based pest management strategies, particularly in developing countries like India.

Limited Knowledge Transfer to Growers : One of the major roadblocks in the adoption of pheromone-based IPM is the lack of awareness and technical know-how among farmers. Many small and marginal farmers are either unfamiliar with the technology or lack the confidence to implement it effectively. This knowledge gap delays adoption, even when pheromone products are available in the market.

To overcome this, targeted extension programs, farmer field schools, and digital advisory platforms such as smartphone apps, SMS alerts and cloud-based pest forecasting tools are being increasingly promoted. These initiatives are helping bridge the knowledge gap by providing farmers with real-time, location-specific advice on the correct deployment, maintenance and interpretation of pheromone trap data.

Regulatory and Market Entry Challenges: Another significant limitation is the disparity in regulatory frameworks governing the approval and distribution of pheromone-based products across countries. The absence of harmonized international standards creates delays and bottlenecks for the commercialization of new formulations, especially in cross-border trade. The solution lies in promoting global collaboration and the harmonization of regulatory standards for pheromone products. Establishing clear, consistent, and science-based protocols for testing, approval and labeling can significantly ease market entry for novel pheromone-based solutions and accelerate their global adoption.

Future Directions and possible scope of research

The field of pheromone-based pest management is rapidly evolving, with innovative research pushing the boundaries of both application and production technologies. The integration of modern genetic, digital and space sciences is expected to redefine the efficiency, scalability, and versatility of pheromone use in pest management — not only for conventional agriculture but also for emerging industrial and scientific applications.

CRISPR-Engineered Insects for Pheromone Biosynthesis : Advancements in genome-editing tools, particularly CRISPR-Cas9, have opened new avenues for engineering insect species capable of synthetic pheromone production. By reprogramming the biosynthetic pathways of specific insects, researchers aim to create living "bioreactors" for pheromone generation. This approach has the potential to eliminate the need for complex chemical synthesis, thereby offering a cost-effective, sustainable, and scalable supply chain for pheromone compounds (Zhang *et al*., 2023). If commercialized, such biotechnological innovations could revolutionize the global pheromone industry, making these tools more accessible to farmers, especially in resource-constrained regions like rural India.

Blockchain for Traceability and Quality Assurance : The integration of blockchain technology into the pheromone supply chain offers promising improvements in traceability, transparency, and quality control. By recording every step of pheromone production, from raw material sourcing to field-level application, blockchain can ensure authentication of product origin, eliminate counterfeit products, and facilitate real-time regulatory compliance (FAO, 2022). This digital infrastructure could also improve farmer confidence and strengthen the market integrity of pheromone-based solutions, especially in large-scale export-driven agriculture systems.

Space-based Applications for Stored Product Protection : The versatility of pheromone-based tools is also under investigation for future space missions, particularly for the long-term protection of stored agricultural products during extraterrestrial expeditions. Closed-loop life support systems in space require pest-free food storage without the use of harmful chemical pesticides. Research initiatives, including those led by NASA, are exploring the adaptation of pheromone-based monitoring and control systems for use in spacecraft and extraterrestrial habitats (NASA, 2021). These studies not only highlight the adaptability of pheromone technology but also pave the way for novel solutions to address pest management challenges in extreme environments.

Conclusion

Pheromone traps have emerged as a highly targeted and environmentally sustainable approach in modern agricultural systems. By mimicking natural chemical communication systems, these traps exploit pest behavior with remarkable precision, allowing for real-time monitoring and direct control. Their species-specific nature ensures minimal environmental impact, conserving natural predators and pollinators, while promoting agro-ecosystem health. Pheromone traps offer a cost-effective and user-friendly option for small and marginal farmers, reducing pesticide dependency and enhancing crop quality and yield. Despite limitations, continued research and region-specific field validation can optimize their effectiveness. As agriculture evolves toward more sustainable practices, pheromone traps are poised to play a crucial role in shaping the future of eco-friendly pest management. Strengthening research, extension services, and farmer training will solidify their role in promoting sustainable agriculture and environmental protection. By integrating pheromone traps with other biological and cultural control measures, farmers can reduce pesticide use, improve crop yields and contribute to a more sustainable food system.

References

Araujo, R.A., Guedes R.N.C., Oliveira M.G.A. and Ferreira G.H. (2013). Enhanced activity of carbohydrate- and lipid-metabolizing enzymes in insecticide-resistant populations of the maize weevil, Sitophilus zeamais. *Bull. Entomological Res.*, **103(4)**, 417–424. https://doi.org/10.1017/S0007485312000768

Benelli, G., Lucchi A., Thomson D. and Ioriatti C. (2020). Sex pheromone aerosol devices for mating disruption: Challenges and prospects. *Pest Manage. Sci.*, **76(1)**, 25–35. https://doi.org/10.1002/ps.5586

Blomquist, G.J. and Bagnères A.G. (2010). *Insect hydrocarbons: Biology, biochemistry, and chemical ecology*. Cambridge

University Press.

Brennan, E.B. (2016). Agroecological pest management in organic farming. *Annu. Rev. Entomol.*, **61**, 355-375.

Butenandt, A. (1959). Über den Sexual-Lockstoff des Seidenspinners Bombyx mori: Reindarstellung und Konstitution. *Zeitschrift für Naturforschung B*, **14(4)**, 283–284. https://doi.org/10.1515/znb-1959-0401

Campos, M.R., Rodrigues A.R.S., Silva W.M., Silva T.B.M., Silva V.R.F., Guedes R.N.C. and Siqueira H.A.A. (2021). Spinosyn resistance in the tomato borer *Tuta absoluta*: Biochemical and biological analyses. *Pest Manage. Sci.*, **77(3)**, 1463–1472. https://doi.org/10.1002/ps.6168

Cardé, R.T. and Millar J.G. (2009). *Advances in insect chemical ecology*. Cambridge University Press.

Cardé, R.T. and Minks A.K. (1995). Control of moth pests by mating disruption: Successes and constraints. *Annu. Rev. Entomol.*, **40(1)**, 559-585.

Carlson, D.A., Mayer M.S., Silhacek D.L., James J.D., Beroza M. and Bierl B.A. (1971). Sex attractant pheromone of the house fly: Isolation, identification and synthesis. *Science*, **174(4004)**, 76-78. https://doi.org/10.1126/science.174.4004.76

Chaudhary, S., Kanwar R.K., Sehgal A. and Kanwar J.R. (2016). Advances in pheromone trapping and lure development for stored product pests. *J. Stored Prod. Res*., **68**, 83–96. https://doi.org/10.1016/j.jspr.2016.05.003

Cork, A., Alam S.N., Rouf F.M.A. and Talekar N.S. (2005). Development of mass trapping technique for control of brinjal fruit and shoot borer, *Leucinodes orbonalis* Guenée (Lepidoptera: Pyralidae). *Bull. Entomological Res.*, **95(6)**, 589–596. https://doi.org/10.1079/BER2005390

Daniel, C. and Baker G. (2013). Pheromone-based monitoring of *Epiphyas postvittana* (Lepidoptera: Tortricidae) in Australian vineyards. *Crop Protection*, **54**, 120–126. https://doi.org/10.1016/j.cropro.2013.08.008

Deutsch, C.A., Tewksbury J.J., Tigchelaar M., Battisti D.S., Merrill S.C., Huey R.B. and Naylor R.L. (2018). Increase in crop losses to insect pests in a warming climate. *Science*, **361(6405)**, 916-919.

Dhir, B.C., Mohapatra H.K. and Senapati B. (2020). Assessment of crop loss in groundnut due to tobacco caterpillar, *Spodoptera litura* (F.). *Indian J. Plant Protect.*, **28(1)**, 15–18.

Dufour, B.P., Fleurat-Lessard F. and Auger J. (2002). Efficacy of traps for *Prostephanus truncatus* and *Sitophilus zeamais* in traditional maize stores in Togo. *J. Stored Prod. Res.*, **38(1)**, 51–61. https://doi.org/10.1016/S0022-474X(01)00006-9

Ekesi, S., Billah M.K., Nderitu P.W., Lux S.A. and Rwomushana I. (2006). Evidence for competitive displacement of *Ceratitis cosyra* by *Ceratitis capitata* (Diptera: Tephritidae) in mango orchards in Kenya. *Annals of the Entomological Society of America*, **99(5)**, 821–830. https://doi.org/10.1603/0013-8746(2006)99[821:EFCDOC]2.0.CO;2

El-Sayed, A.M. (2023). The Pherobase: Database of insect pheromones and semiochemicals. Retrieved from https://www.pherobase.com

El-Sayed, A.M., Suckling D.M., Wearing C.H. and Byers J.A. (2006). Potential of mass trapping for long-term pest management and eradication of invasive species. *J. Econ. Entomol.*, **99(5)**, 1550-1564.

FAO (2022). Blockchain applications in agriculture: Improving transparency and efficiency. Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cb8667en

Fettig, C.J., Klepzig K.D., Billings R.F., Munson A.S., Nebeker T.E., Negrón J.F. and Nowak J.T. (2007). The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. *Forest Ecol. Manage.*, **238(1-3)**, 24–53. https://doi.org/10.1016/j.foreco.2006.10.011

Furlong, M.J., Wright D.J. and Dosdall L.M. (2013). Diamondback moth ecology and management: Problems, progress and prospects. *Annu. Rev. Entomol.*, **58**, 517–541. https://doi.org/10.1146/annurev-ento-120811-153605

Galizia, C.G. and Rössler W. (2010). Parallel olfactory systems in insects: Anatomy and function. Annu. Rev. Entomol., **55**, 399–420. https://doi.org/10.1146/annurev-ento-112408-085442

Gupta, S., Sharma S. and Singh R. (2019). Pheromone-based integrated pest management in soybean: A case study from India. *Crop Protection*, **125**, 104–112. https://doi.org/10.1016/j.cropro.2019.05.003

Hagstrum, D.W. and Subramanyam B. (2009). *Stored-product insect resource*. AACC International.

Hallett, R.H., Gries G., Gries R., Borden J.H., Czyzewska E., Oehlschlager A.C. and Pierce H.D. (2004). Aggregation pheromones of two Asian palm weevils, *Rhynchophorus ferrugineus* and *R. vulneratus*. *Naturwissenschaften*, **91(7)**, 324–327. https://doi.org/10.1007/s00114-004-0529-5

Hansson, B.S. and Anton S. (2000). Function and morphology of the antennal lobe: New developments. *Annual Rev. Entomol.*, **45**, 203–231. https://doi.org/10.1146/annurev.ento.45.1.203

Ioriatti, C., Anfora G., Angeli G., Civolani S., Schmidt S., Pasqualini E. and Mazzoni V. (2011). *Lobesia botrana* (Lepidoptera: Tortricidae) mating disruption: Effect of pheromone formulations and concentrations. *J. Econ. Entomol.*, **104(5)**, 1519–1527. https://doi.org/10.1603/EC11041

Jactel, H., Verheggen F., Thiéry D., Escobar-Gutiérrez A.J., Gachet E. and Desneux N. (2019). Non-consumptive effects of natural enemies on phytophagous insects: A review. *J. Pest Sci.*, **92(3)**, 1009–1022. https://doi.org/10.1007/s10340-019-01095-8

Jaffe, B.D., Guédot C. and Avila G.A. (2019). Automated pest monitoring systems in agriculture: Current status and future prospects. *J. Pest Sci.*, **92(1)**, 1-12.

Jurenka, R. (2004). Insect pheromone biosynthesis. *Topics Curr. Chem.*, **239**, 97-132. https://doi.org/10.1007/b95450

Karlson, P. and Lüscher M. (1959). Pheromones: A new term for a class of biologically active substances. *Nature*, **183(4653)**, 55-56.

Katti, G., Pasalu I.C. and Krishnaiah N.V. (2001). Pheromone-based management of yellow stem borer, *Scirpophaga incertulas* (Walker), in rice. *Int. Rice Res. Notes*, **26(2)**, 34–35.

Kishimoto, T., Adachi I., Maeda T. and Kainoh Y. (2008). Sex pheromone of the persimmon fruit moth, *Stathmopoda masinissa* (Lepidoptera: Stathmopodidae). *Appl. Entomol. Zool.*, **43(2)**, 227–233. https://doi.org/10.1303/aez.2008.227

Knight, A.L., Light D.M. and Trimble R.M. (2014). Identifying *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae) neonate larval attractants for improved monitoring and control. *Pest Manage. Sci.*, **70(1)**, 159–166. https://doi.org/10.1002/ps.3549

Kogan, M. (1998). Integrated pest management: Historical perspectives and contemporary developments. *Annu. Rev. Entomol.*, **43(1)**, 243-270.

Kumar, P., Mishra S., Malik A. and Satya S. (2017). Insecticidal properties of Mentha species: A review. *Industrial Crops and Products*, **103**, 144–155. https://doi.org/10.1016/j.indcrop.2017.03.034

Leal, W.S. (2013). Odorant reception in insects: Roles of receptors, binding proteins, and degrading enzymes. *Annu. Rev. Entomol.*, **58**, 373–391. https://doi.org/10.1146/annurev-ento-120811-153635

Löfstedt, C. (1993). Moth pheromone genetics and evolution. *Philosophical Trans. Royal Soc. B: Biolog. Sci.*, **340(1292)**, 167–177. https://doi.org/10.1098/rstb.1993.0055

Lucchi, A., Ladurner E., Iodice A., Savino F., Ricciardi R. and Cosci F. (2018). Sustainable control of Lobesia botrana in vineyards: A review of pheromone-based strategies. *Agricult., Ecosyst. Environ.*, **265**, 12–22. https://doi.org/10.1016/j.agee.2018.05.026

Mangan, R.L., Moreno D.S. and Thompson G.D. (2006). Bait dilution, spinosad concentration, and efficacy of GF-120 based fruit fly sprays. *Crop Protection*, **25(2)**, 125–133. https://doi.org/10.1016/j.cropro.2005.03.012

Markets and Markets (2023). Insect pheromones market by type (sex, aggregation, alarm), application (detection & monitoring, mass trapping, mating disruption), crop type (fruits & nuts, vegetables, cereals & grains), and region—Global forecast to 2028.

Mazomenos, B.E., Pantazi-Mazomenou A. and Stefanou D. (2002). Attract-and-kill strategy for controlling the olive fruit fly, *Bactrocera oleae*, in Greece. *J. Econ. Entomol.*, **95(2)**, 336–343. https://doi.org/10.1603/0022-0493-95.2.336

Miller, J.R. and Gut L.J. (2015). Mating disruption for the 21st century: Matching technology with mechanism. *J. Chemical Ecol.*, **41(7)**, 567-581.

Mills, N.J., Beers E.H., Shearer P.W., Unruh T.R. and Amarasekare K.G. (2016). Comparative analysis of pesticide effects on natural enemies in western orchards: A synthesis. *Pest Manage. Sci.*, **72(5)**, 787–796. https://doi.org/10.1002/ps.4146

Minks, A.K. and van der Kraan C. (2005). Behavior-modifying chemicals: Prospects and constraints in IPM. In: *Integrated Pest Management* (pp. 73-86). Springer.

NASA (2021). Advanced life support systems for long-duration space missions. National Aeronautics and Space Administration.

Navarro-Llopis, V., Alfaro C., Primo J. and Vacas S. (2008). Evaluation of traps and lures for mass trapping of Mediterranean fruit fly in citrus groves. *J. Econ. Entomol.*, **101(1)**, 126–131. https://doi.org/10.1093/jee/101.1.126

Norin, T. (2007). Pheromones and other semiochemicals for pest control. *Chemical Reviews*, **107(9)**, 3746-3762.

Patil, R.K. and Vyakarnahal B.S. (2001). Management of sesame leaf webber, *Antigastra catalaunalis* (Duponchel), using pheromone traps. *J. Oilseeds Res.*, **18(1)**, 120–123.

Potamitis, I., Rigakis I. and Fysarakis K. (2017). Automated remote insect surveillance at a global scale and the Internet of Things. *Robotics*, **6(3)**, 19. https://doi.org/10.3390/robotics6030019

Pureswaran, D.S., Roques A. and Battisti A. (2018). Forest insects and climate change. *Current Forestry Reports*, **4(2)**, 35-50.

Reddy, G.V.P. and Guerrero A. (2004). Interactions of insect pheromones and plant semiochemicals. *Trends in Plant Sci.*, **9(5)**, 253–261. https://doi.org/10.1016/j.tplants.2004.03.009

Reddy, G.V. and Guerrero A. (2004). Interactions of insect pheromones and plant semiochemicals. *Trends in Plant Sci.*, **9(5)**, 253-261.

Röck, F., Barsan N. and Weimar U. (2008). Electronic nose: Current status and future trends. *Chemical Reviews*, **108(2)**, 705–725. https://doi.org/10.1021/cr068121q

Roelofs, W.L., Hill A.S., Cardé R.T. and Baker T.C. (1973). Two sex pheromone components of the tobacco budworm moth, *Heliothis virescens*. *Life Sciences*, **13(5)**, 373-381. https://doi.org/10.1016/0024-3205(73)90120-8

Sato, K. and Touhara K. (2009). Insect olfactory receptors: Function and regulation. *Curr. Opinion Insect Sci.*, **1(1)**, 1–7. https://doi.org/10.1016/j.cois.2014.05.001

Scholtz, C.H. and Schöller M. (2018). Pheromone-based monitoring of stored product pests: A review. *J. Pest Sci.*, **91(3)**, 1005–1020. https://doi.org/10.1007/s10340-018-0970-4

Sharma, H.C. and Varma A. (1993). Pheromone traps for monitoring *Chilo infuscatellus* (Lepidoptera: Pyralidae) in sugarcane. *J. Econ. Entomol.*, **86(4)**, 1029–1034. https:/

/doi.org/10.1093/jee/86.4.1029

Shylesha, A.N., Jalali S.K., Gupta A., Varshney R. and Venkatesan T. (2006). Record of Trichogramma chilonis parasitizing eggs of *Maruca vitrata* on pigeonpea. *J. Biological Control*, **20(2)**, 227–228.

Singh, R., Kumar P. and Sharma S. (2014). Pheromone-based management of sugarcane borers: A case study from India. *Sugar Tech.*, **16(4)**, 412–420. https://doi.org/10.1007/s12355-014-0319-0

Sparks, T.C. and Nauen R. (2015). IRAC: Mode of action classification and insecticide resistance management. *Pesticide Biochem. Physiol.*, **121**, 122-128.

Srinivasan, R. (2008). Integrated pest management for eggplant fruit and shoot borer (*Leucinodes orbonalis*). *J. Plant Protect. Res*., **48(3)**, 303–312. https://doi.org/10.2478/v10045-008-0041-6

Stathas, G.J., Eliopoulos P.A., Kontodimas D.C. and Saitanis C.J. (2012). Evaluation of pheromone traps for monitoring *Lasioderma serricorne* (Coleoptera: Anobiidae) in tobacco stores. *J. Econ. Entomol.*, **105(3)**, 905–911. https://doi.org/10.1603/EC11350

Subramanyam, B. and Hagstrum D.W. (2000). *Alternatives to pesticides in stored-product IPM*. Kluwer Academic Publishers.

Symonds, M.R.E. and Elgar M.A. (2008). The evolution of pheromone diversity. *Trends Ecol. Evol.*., **23(4)**, 220-228. https://doi.org/10.1016/j.tree.2007.11.009

Tabashnik, B.E., Sisterson M.S., Ellsworth P.C., Dennehy T.J., Antilla L., Liesner L. and Carrière Y. (2010). Suppressing resistance to Bt cotton with sterile insect releases. *Nat. Biotechnol*., **28(12)**, 1304–1307. https://doi.org/10.1038/nbt.1704

Tillman, J.A., Seybold S.J., Jurenka R.A. and Blomquist G.J. (1999). Insect pheromones—an overview of biosynthesis and endocrine regulation. *Insect Biochem. Mole. Biol.*, **29(6)**, 481-514. https://doi.org/10.1016/S0965-1748(99)00016-8

Trematerra, P. (2012). Advances in the use of pheromones for stored-product protection. *J. Pest Sci.*, **85(1)**, 133–146. https://doi.org/10.1007/s10340-011-0407-9

Vargas, R.I., Piñero J.C. and Leblanc L. (2010). An overview of pest species of *Bactrocera* fruit flies (Diptera: Tephritidae) and the integration of biopesticides with other biological approaches for their management with a focus on the Pacific region. *Insects*, **1(1)**, 1–20. https://doi.org/10.3390/insects1010001

Wightman, J.A. and Ranga Rao G.V. (1993). Groundnut pests and their management. *Int. J. Pest Manage*., **39(4)**, 443–450. https://doi.org/10.1080/09670879309371823

Witzgall, P., Kirsch P. and Cork A. (2010). Sex pheromones and their impact on pest management. *J. Chemical Ecol.*, **36(1)**, 80–100. https://doi.org/10.1007/s10886-009-9737-y

Wyatt, T.D. (2014). Pheromones and animal behavior: Chemical signals and signatures. Cambridge University Press.

Wyatt, T.D. (2020). *Pheromones and animal behavior: Chemical signals and signatures* (2nd ed.). Cambridge University Press.

Zhang, L., Zhang Y. and Zhang J. (2021). Drone-based precision pest management: Current status and future prospects. *Computers and Electronics in Agriculture*, **182**, 106–115. https://doi.org/10.1016/j.compag.2021.106115

Zhang, X., Li Y. and Wang Z. (2023). CRISPR-based engineering of insect pheromone biosynthesis pathways. *Nat. Biotechnol.*, **41(2)**, 145–152. https://doi.org/10.1038/s41587-022-01580-z