**Insect behaviour modulation using pheromones: Trends and Applications**

**Abstract:**

Pheromones are chemical signals secreted by insects that influence the behavior of conspecifics, playing a pivotal role in communication related to mating, aggregation, foraging, and defense. This review explores the advances in understanding insect behavioral modulation through pheromones, with a focus on contemporary trends and real-world applications. Emphasis is placed on the ecological functions of various pheromone types, mechanisms of detection, and behavioral outcomes. Emerging technologies in pheromone synthesis, controlled release systems, and gene-editing for pheromone production are also discussed. Practical applications such as mating disruption, mass trapping, lure-and-kill strategies, and integrated pest management (IPM) highlight the potential of pheromones in sustainable agriculture. The paper further outlines challenges including pheromone degradation, species-specificity, and resistance. By integrating ecological insights with biotechnological innovations, pheromone-based approaches offer a promising, eco-friendly alternative to conventional insecticides, reducing environmental impact while enhancing crop protection.

**Keywords:** Insect pheromones**,** Behavioural modulation**,** Semiochemicals**,** Mating disruption**,** Integrated pest management (IPM)**,** Mass trapping**,** Lure-and-kill**,** Sustainable pest control

**1. Introduction**

Insects represent the most diverse and ecologically successful group of organisms on Earth. Their dominance is largely driven by complex communication systems, with chemical signaling—particularly through pheromones—playing a central role in coordinating social and survival behaviors. (1,2) Pheromones are defined as species-specific chemical substances secreted externally by an individual, which trigger innate behavioral or physiological responses in other members of the same species.(2,3) These signals govern a wide spectrum of activities including mate location, aggregation, trail-following, alarm signaling, and defense mechanisms.(3,4)

Over the past several decades, scientific exploration into insect pheromones has expanded, aided by developments in analytical chemistry, behavioral ecology, electrophysiology, and molecular biology. (5,6)The identification, characterization, and synthetic replication of pheromones have opened new avenues for pest control, especially in agriculture.(2,6) Unlike traditional insecticides, pheromone-based methods are target-specific, non-toxic, environmentally benign, and often compatible with organic and integrated pest management (IPM) practices. (5,6)

The growing global concern over pesticide resistance, environmental contamination, and biodiversity loss has made pheromone-based control strategies increasingly attractive. (7,8) Techniques such as mating disruption, mass trapping, and lure-and-kill systems exploit the natural communication channels of insects, thereby interrupting their reproductive cycles or directing them away from valuable crops. These interventions are not only effective but are often economically sustainable in the long run due to their specificity and reduced environmental costs.(5,7)

By connecting ecological insights with advanced biotechnological tools, pheromone-mediated behavior modulation represents a forward-thinking, sustainable approach to pest control that aligns with both agricultural productivity and environmental stewardship.(4,9)

## ****2. Types of Insect Pheromones****

Insect pheromones are classified based on their biological function and the type of behavioral or physiological response they elicit in the recipient. Understanding the types of pheromones is crucial for designing effective strategies to manipulate insect behavior for ecological or pest management purposes.(10,11) Broadly, insect pheromones are categorized into the following types:

### 2.1. ****Sex Pheromones****

These are among the most studied pheromones and play a critical role in mating behavior. Typically produced by females (though in some species by males), sex pheromones are released into the environment to attract mates over long distances. For instance, in the moth Helicoverpa armigera, females emit a blend of volatile compounds that males detect with highly specialized olfactory receptors. These pheromones are central to mating disruption and mass trapping strategies in pest management. (12,13)

### 2.2. ****Aggregation Pheromones****

These pheromones lead to the clustering of individuals, often for feeding, mating, or protection. Unlike sex pheromones, aggregation pheromones are usually produced by both sexes. A well-known example is the red flour beetle (Tribolium castaneum), which emits an aggregation pheromone that attracts conspecifics to a food source. These are exploited in lure-and-kill and push-pull systems. (12,13)

### 2.3. ****Alarm Pheromones****

Alarm pheromones are released in response to predation or disturbance and cause immediate escape or aggressive behavior in conspecifics. They are common in eusocial insects such as ants, bees, and aphids. For example, when attacked, aphids release (E)-β-farnesene, prompting others to flee. These pheromones have been considered for crop protection by triggering avoidance behaviors in pest species.(11,13)

### 2.4. ****Trail Pheromones****

Used predominantly by ants and termites, trail pheromones help mark paths to food sources or new nesting sites. These chemicals are continuously deposited by foragers and followed by other colony members. Their stability and renewal frequency influence foraging efficiency. Synthetic trail pheromones can be used to manipulate movement patterns of invasive species. (12,14)

### 2.5. ****Primer vs. Releaser Pheromones****

Releaser pheromones trigger immediate behavioral responses, such as mating or aggregation.

Primer pheromones, on the other hand, induce long-term physiological or hormonal changes. For instance, the queen mandibular pheromone (QMP) in honeybees suppresses worker reproduction and maintains social hierarchy. (13,14)

## ****3. Pheromone Perception and Signal Processing****

The detection and interpretation of pheromones in insects are mediated through highly specialized and finely tuned sensory and neural mechanisms. The success of pheromone-mediated behavior depends on the sensitivity, specificity, and speed with which an insect can recognize and respond to chemical cues in its environment. This section outlines the structural and functional basis of pheromone perception and the downstream neural processing that ultimately leads to behavioral outcomes. (15,16)

### 3.1. ****Olfactory Sensilla and Antennal Receptors****

Insects detect pheromones primarily through their antennae, which are equipped with numerous sensilla—microscopic hair-like structures containing olfactory receptor neurons (ORNs). These neurons are embedded in the cuticle and bathed in sensillar lymph, where odorant-binding proteins (OBPs) help solubilize hydrophobic pheromone molecules and transport them to olfactory receptors (ORs) on the neuron membranes. The specificity of the ORs determines the insect’s ability to distinguish between closely related pheromonal compounds, which is critical for species-specific communication. (17,18)

### 3.2. ****Pheromone Receptors and Signal Transduction****

Upon binding of a pheromone to its corresponding receptor, a cascade of signal transduction events is initiated. These typically involve G-protein coupled receptors (GPCRs), which activate intracellular second messengers such as cAMP or IP₃, leading to depolarization of the neuron and the generation of action potentials. In many insect species, pheromone detection systems are tuned to nanogram or even picogram sensitivity, enabling long-distance detection. (17,19)

### 3.3. ****Neural Processing in the Antennal Lobe****

Once detected, the electrical signals from ORNs are transmitted to the antennal lobe, the primary olfactory center in the insect brain. Here, the information is spatially and chemically organized into glomeruli, each receiving input from ORNs expressing the same receptor. The antennal lobe processes the signal through local interneurons and projection neurons, allowing for contrast enhancement, signal amplification, and initial coding of intensity and blend composition. (20,21)

### 3.4. ****Integration in Higher Brain Centers****

Signals from the antennal lobe are then relayed to higher brain centers such as the mushroom bodies and lateral protocerebrum, where they are integrated with other sensory inputs and memory circuits. This integration helps modulate context-dependent behaviors, such as flight orientation toward a pheromone plume or decision-making in mating or avoidance. (22,23)

### 3.5. ****Species Specificity and Sensory Adaptations****

Insects have evolved a wide range of adaptations to ensure species-specific pheromone recognition. These include unique combinations of receptor proteins, temporal coding of signal pulses, and behavioral thresholds that prevent cross-attraction with closely related species. In agricultural pest management, exploiting this specificity is essential for targeted pest control without affecting beneficial insects. (16,19)

Understanding the perception and processing of pheromones provides the mechanistic foundation for designing effective pheromone-based interventions, including biosensors, synthetic analogs, and genetically modified traps that mimic natural cues. (18,21)

## ****4. Mechanisms of Behavioural Modulation****

Pheromones are not merely chemical cues—they are powerful modulators of insect behavior, capable of eliciting rapid and often stereotyped responses that are critical for survival, reproduction, and social organization. The mechanisms by which insects translate pheromone signals into behavior involve tightly regulated neural and endocrine pathways. This section explores the key behavioral processes influenced by pheromones and the underlying biological systems that mediate these changes.(22,23)

### 4.1. ****Mate Attraction and Courtship Behavior****

Sex pheromones are essential for mate location and selection in many insect species. Typically, females release volatile sex pheromones into the environment, which attract conspecific males over long distances. Upon detection, males orient toward the pheromone source using anemotaxis (wind-directed movement). The final stages of courtship often involve close-range contact pheromones, which confirm species identity and readiness to mate. This two-tiered signaling system ensures reproductive success and minimizes hybridization with other species. (23,24)

### 4.2. ****Aggregation and Group Behavior****

Aggregation pheromones induce insects of both sexes and multiple developmental stages to assemble in a particular area. This behavior is common in species such as bark beetles and locusts, where coordinated mass behavior aids in survival, feeding, or reproduction. The release of aggregation pheromones can trigger positive feedback loops, where each new arrival contributes to further release and attraction, resulting in rapid population clustering. These dynamics are leveraged in mass-trapping strategies for pest control. (19,25)

### 4.3. ****Alarm and Defensive Responses****

Alarm pheromones are rapidly released in response to threats and provoke immediate defensive or evasive behaviors in nest-mates or conspecifics. In aphids, the release of alarm pheromones causes others to drop from the plant to escape predation. In social insects like ants and bees, alarm pheromones trigger aggressive defense responses and recruitment of nest-mates to the source of disturbance. These pheromones often act within seconds and degrade quickly to prevent prolonged unnecessary activation. (26,27)

### 4.4. ****Foraging and Resource Localization****

Pheromones also guide foraging behavior, especially in social insects. Trail pheromones enable worker ants and termites to locate and return to food sources with precision. In solitary insects, kairomones (a subclass of semiochemicals) may guide predators or parasitoids to prey. Some insects use food-marking pheromones to avoid over-exploited resources, a behavior that ensures optimal foraging efficiency within a population. (28,29)

### 4.5. ****Social Regulation in Eusocial Insects****

In colonies of ants, bees, and termites, pheromones regulate caste differentiation, reproduction, and task allocation. Primer pheromones—such as the queen mandibular pheromone in honeybees—have long-term effects on physiology, such as inhibiting ovarian development in workers. These pheromonal systems maintain colony homeostasis and suppress intra-colony conflict, ensuring the success of complex eusocial systems. (30,31)

Understanding these mechanisms provides the behavioral context necessary to develop species-specific pheromone-based interventions that align with natural communication systems, increasing efficacy and minimizing ecological disruption. (32,33)

**5. Pheromone Synthesis and Delivery Systems**

The successful implementation of pheromone-based strategies in insect behavior modulation relies heavily on two critical components: the ability to synthesize pheromones with high chemical fidelity and the development of effective delivery systems that can release these compounds in a controlled and sustained manner. In nature, pheromones are synthesized by insects in specialized exocrine glands, often located near the abdomen or thorax, such as the sex pheromone glands in female moths or the Dufour's glands in social insects like ants. The biosynthesis of these chemical signals is typically regulated by hormonal cues, including juvenile hormone and pheromone biosynthesis-activating neuropeptide (PBAN), which coordinate the timing and quantity of pheromone production. (19,28)

In applied contexts, however, reliance on natural extraction is neither scalable nor cost-effective. Hence, synthetic organic chemistry plays a central role in the industrial production of insect pheromones. (20,24)Chemical synthesis involves a series of carefully orchestrated reactions such as esterification, isomer-specific hydrogenation, and chain elongation to produce pheromones with precise stereochemistry. Maintaining the enantiomeric purity of these compounds is essential because even minor variations in molecular structure can lead to complete loss of activity or unintended effects on non-target species. In recent years, biotechnological advances have paved the way for microbial production of pheromones using genetically engineered organisms like yeast or E. coli. These systems allow for cost-effective and environmentally friendly synthesis through fermentation, offering a sustainable alternative to traditional chemical methods. (27,28)

Once synthesized, pheromones must be delivered into the environment in a manner that mimics natural release patterns. (19,23) This is particularly important for ensuring the efficacy of strategies like mating disruption and mass trapping. Various formulation technologies have been developed to achieve this goal. Common delivery mechanisms include rubber septa, polyethylene vials, and wax-based dispensers that gradually release pheromones over time. Microencapsulation has emerged as a leading technique, where pheromone molecules are embedded within a polymer matrix that controls their diffusion rate. (23,25) These slow-release formulations help maintain consistent pheromone concentrations in the field, reduce the need for frequent re-application, and are often biodegradable, aligning with organic farming practices.(27,28)

Advancements in application technologies have further expanded the effectiveness of pheromone-based methods. In orchards, grid-like networks of dispensers can saturate the environment with synthetic pheromones, confusing male insects and preventing successful mating. For larger-scale deployments, automated aerosol devices, often referred to as puffers, emit timed bursts of pheromone into the air and can be programmed based on pest activity patterns. Bait stations that combine pheromones with toxicants are used in lure-and-kill strategies, which offer targeted action with minimal pesticide use. Sprayable pheromone formulations have also gained popularity, especially among small-scale farmers, as they allow for convenient application using conventional spraying equipment. (29,31)

An exciting frontier in pheromone delivery lies in smart technologies and precision agriculture. Researchers are now exploring Internet of Things (IoT)-enabled traps and dispensers that respond to real-time environmental cues or pest population data. These systems promise dynamic and adaptive pheromone release, improving both efficiency and resource utilization. (30,31) As the cost of these technologies decreases, they are likely to become more accessible to farmers worldwide.(32,33)

**6. Applications in Pest Management**

The use of pheromones in pest management has become a cornerstone of environmentally conscious agricultural practices. Unlike conventional insecticides, which often pose risks to human health, non-target organisms, and the environment, pheromone-based strategies offer a highly specific and sustainable alternative. (34,35) By mimicking natural chemical communication signals, these methods can manipulate pest behavior in a way that disrupts population growth and reduces crop damage without contributing to pesticide resistance or environmental contamination. (36,37)

One of the most widely adopted pheromone applications is mating disruption. In this method, synthetic sex pheromones are released in the crop environment at concentrations sufficient to confuse male insects and prevent them from locating females. (38,39) This leads to a significant reduction in mating success, egg laying, and, ultimately, pest population density. Mating disruption has been effectively used against several major agricultural pests such as *Cydia pomonella* (codling moth), *Grapholita molesta* (oriental fruit moth), and *Spodoptera litura* (tobacco cutworm), particularly in fruit orchards and vegetable crops. (40,41)

Another practical use of pheromones is in mass trapping. Here, pheromone lures are placed inside traps to attract and capture large numbers of pests, thereby directly reducing their population. This method is especially valuable for monitoring and controlling low to moderate pest infestations and is commonly used for stored product insects, bark beetles, and certain lepidopteran pests. The success of mass trapping depends on careful calibration of trap design, pheromone blend composition, and trap density. (42,43)

The lure-and-kill strategy integrates pheromones with toxic agents. In this approach, insects are attracted to a source containing both the pheromone and a pesticide or biological agent. Upon contact or ingestion, the pest is killed. This technique minimizes the amount of pesticide used and confines its application to specific points of action, thereby reducing ecological harm. Lure-and-kill systems have proven effective in managing fruit flies and cotton bollworms in several cropping systems. (41,42)

In addition to direct suppression techniques, pheromones are essential in pest monitoring and early detection. By using pheromone-baited traps, farmers and pest control agencies can estimate population levels, track seasonal dynamics, and make informed decisions about intervention thresholds. This monitoring enables timely and precise pest management, improving efficiency and minimizing unnecessary pesticide applications. (43, 44)

Pheromones also play a vital role in integrated pest management (IPM) programs. When combined with biological control agents, cultural practices, and mechanical interventions, pheromone-based tools enhance the overall robustness and sustainability of pest control systems. Their species-specific nature ensures minimal disruption to natural enemies and pollinators, supporting ecosystem balance. (45,46)

In recent years, there has been growing interest in applying pheromone strategies beyond agriculture. Urban pest control programs, forestry management, and vector control campaigns have begun to incorporate pheromone technologies, expanding their impact. As new synthesis methods and smart delivery systems emerge, pheromone-based approaches are expected to become even more accessible and versatile across diverse ecological settings. (38,41)

**7. Recent Trends and Emerging Technologies**

The field of pheromone-based insect behavior modulation has entered a new era, driven by technological innovation, interdisciplinary research, and an urgent global demand for sustainable pest control solutions. What was once a niche technique limited to a few high-value crops is now expanding rapidly due to breakthroughs in synthetic biology, digital agriculture, and environmental monitoring systems. (42,43) These developments are enhancing both the accessibility and the precision of pheromone applications in integrated pest management.

One of the most significant advancements in recent years is the application of synthetic biology to pheromone production. (44,45) By genetically engineering microorganisms such as yeast or bacteria, researchers have successfully developed biological factories capable of producing complex pheromone molecules through fermentation. These bio-based pheromones offer a scalable and environmentally sustainable alternative to conventional chemical synthesis, which can be costly and resource-intensive. (46,47) Moreover, the microbial production systems allow for fine-tuning of pheromone blends and enantiomeric purity, ensuring species-specificity and high efficacy in field applications. (48,49)

Alongside biotechnological innovations, there has been rapid growth in the development of smart delivery systems. Traditional dispensers, though effective, are limited by their passive nature and fixed release rates. In contrast, modern systems incorporate microcontrollers, sensors, and actuators to dynamically control pheromone emission based on environmental cues such as temperature, humidity, and pest activity. These automated aerosol devices can be programmed to release pheromones during peak insect activity periods, significantly improving efficiency while minimizing wastage. Integration with GPS and weather forecasting tools further enables farmers to customize pheromone application across spatial and temporal scales. (49,50)

Digital agriculture is also playing an increasingly important role in the monitoring and deployment of pheromone-based tools. Remote sensing technologies, coupled with pheromone-baited traps, can provide real-time data on pest population dynamics. Artificial intelligence and machine learning algorithms are being employed to analyze these data streams, predict pest outbreaks, and generate early warnings. These predictive models support more informed decision-making, reduce the need for prophylactic pesticide use, and optimize the timing of pheromone-based interventions. (47,51)

Another emerging trend is the exploration of pheromones in non-agricultural settings. Urban pest management, public health vector control, and forest protection are now adopting pheromone-based solutions. For example, research is underway to use pheromone traps to monitor and control mosquito populations, which could revolutionize vector-borne disease prevention strategies. In forestry, pheromone-based mass trapping is being applied to manage bark beetle outbreaks, offering an eco-friendly alternative to tree felling or insecticide sprays. (48,52)

Despite these promising developments, challenges remain. The cost of smart delivery systems can be prohibitive for smallholder farmers, and there is still a need for regulatory harmonization to facilitate the approval and commercialization of bio-synthesized pheromones. Nevertheless, the convergence of biology, chemistry, engineering, and information technology is rapidly transforming the landscape of pheromone-based pest control. As these innovations mature and become more widely adopted, they are poised to make pheromone technologies more effective, affordable, and globally applicable than ever before. (43,51)

**8. Challenges and Limitations**

Despite the significant progress in pheromone-based technologies for insect behavior modulation, several challenges continue to limit their widespread adoption and consistent effectiveness across different ecological and agricultural systems.(52,53) These limitations span biological, technological, economic, and regulatory domains and must be addressed to unlock the full potential of pheromone applications in integrated pest management. (54,55)

One of the primary biological challenges lies in the species-specific nature of pheromones. While this specificity is an advantage for targeted pest control, it also means that separate formulations and delivery strategies must be developed for each pest species. This increases research and development costs and complicates logistics, particularly for farmers managing multiple pest species simultaneously. Additionally, the chemical composition of pheromones can vary across populations due to geographic and genetic differences, requiring localized calibration of pheromone blends to ensure efficacy. (54,56)

Environmental factors such as temperature, wind, humidity, and ultraviolet radiation also influence the stability and dispersal of pheromone compounds in the field. High temperatures can accelerate pheromone volatilization, reducing their active duration, while rain and UV exposure can degrade active compounds. (52,53) These factors necessitate the development of advanced formulations with improved stability and controlled-release mechanisms, which may raise costs and require more sophisticated deployment. (54,55)

Another concern is the potential for pheromone habituation or resistance in insect populations. Although rare compared to conventional insecticide resistance, repeated and prolonged exposure to synthetic pheromones can lead to behavioral desensitization or altered mating behaviors in some species. Monitoring these trends is essential to prevent long-term efficacy loss and maintain the integrity of pheromone-based strategies. (50,51)

From a technological perspective, the high cost of synthesis, especially for multi-component or chiral pheromones, remains a barrier, particularly for smallholder and resource-limited farmers. While bio-fermentation and synthetic biology are beginning to reduce costs, these technologies are still in transition from lab-scale to commercial production and are subject to scalability and purity challenges. (48,49)

There are also regulatory and market-related hurdles. The registration process for pheromone products can be time-consuming and inconsistent across regions, with differing safety assessment requirements, data standards, and labeling regulations. (50,57) Furthermore, limited awareness among farmers and extension agents about pheromone technologies and how to implement them effectively often leads to underutilization or incorrect application, reducing their impact.

Lastly, integrating pheromone-based tools into existing pest management frameworks requires coordination with other control methods, including biological agents and cultural practices. Poor integration or incompatible application timing can reduce overall program effectiveness. Therefore, training, education, and stakeholder collaboration are essential components for maximizing the success of these technologies.(51,58)

**9. Conclusion**

The modulation of insect behavior through pheromones represents one of the most ecologically intelligent and scientifically elegant approaches to pest management. Over the past few decades, advances in the understanding of pheromone chemistry, perception mechanisms, and behavioral outcomes have not only deepened our knowledge of insect ecology but have also translated into a range of practical, sustainable applications in agriculture, forestry, and public health. As global concerns around pesticide resistance, environmental contamination, and biodiversity loss continue to intensify, pheromone-based strategies provide a powerful alternative—one that aligns with the goals of precision farming, ecological stewardship, and food security.

This review has explored the multifaceted roles of pheromones in regulating insect behavior, highlighting their types, modes of perception, and applications in mating disruption, mass trapping, and lure-and-kill systems. It has also emphasized the importance of synthesis and delivery technologies, emerging biotechnological innovations, and smart agriculture solutions that are reshaping how we deploy semiochemicals in the field. While the potential is immense, challenges such as cost, regulatory complexity, formulation stability, and species-specific calibration still hinder widespread implementation, especially in smallholder farming systems.

Looking ahead, the integration of pheromone technology with digital tools, microbial biosynthesis platforms, and environmentally adaptive delivery systems is expected to enhance both accessibility and efficacy. Continued investment in research, education, and cross-sector collaboration will be essential for overcoming existing barriers and enabling pheromone-based solutions to become mainstream components of global pest management strategies.

Ultimately, pheromone-mediated insect behavior modulation offers a rare convergence of ecological harmony and agricultural productivity. By continuing to refine and scale these tools, we can move closer to a future where pest control is not only effective but also sustainable, selective, and in tune with the natural world.

**References**

1. Mahajan, U. V., & Kawale, S. S. (2023). Semi Chemical Communication: a Sustainable Approach for Suppressing Insect Pests Population. *International Journal of Agricultural Science*, *8*.
2. Gaddanakeri, K. P., & Kumar, A. Role of Semio-Chemicals In Pest Management. *ADVANCEMENTS IN PLANT PROTECTION*, 155.
3. Reddy, G. V., Sharma, A., & Guerrero, A. (2020). Advances in the use of semiochemicals in integrated pest management: pheromones. In *Biopesticides for sustainable agriculture* (pp. 251-282). Burleigh Dodds Science Publishing.
4. Abd El-Ghany, N. M. (2020). Pheromones and chemical communication in insects. *Pests, weeds and diseases in agricultural crop and animal husbandry production*, 1-13.
5. Kumar, N., Naveen, G., Padhan, S., Hembram, S., Rathore, T., Mohanta, S., & Mani, a. Pheromone traps in insect pest management: a comprehensive review of their applications, efficacy and future directions in integrated pest management.
6. Rizvi, S. A. H., George, J., Reddy, G. V., Zeng, X., & Guerrero, A. (2021). Latest developments in insect sex pheromone research and its application in agricultural pest management. *Insects*, *12*(6), 484.
7. Rizvi, S. A. H., George, J., Reddy, G. V., Zeng, X., & Guerrero, A. (2021). Latest developments in insect sex pheromone research and its application in agricultural pest management. *Insects*, *12*(6), 484.
8. Rizvi, S. A. H., George, J., Reddy, G. V., Zeng, X., & Guerrero, A. (2021). Latest developments in insect sex pheromone research and its application in agricultural pest management. *Insects*, *12*(6), 484.
9. Guerrero, A., & Reddy, G. V. (2023). Chemical Communication in Insects: New Advances in Integrated Pest Management Strategies. *Insects*, *14*(10), 799.
10. Regnier, F. E., & Law, J. H. (1968). Insect pheromones. *Journal of lipid research*, *9*(5), 541-551.
11. Meenambigai, C., & Samanta, S. (2023). Insect Communication: Chemical Signals and Pheromones. In *Entomology Redefined* (pp. 190-210). CRC Press.
12. Wyatt, T. D. (2010). Pheromones and behavior. In *Chemical communication in crustaceans* (pp. 23-38). New York, NY: Springer New York.
13. Basu, S., Clark, R. E., Fu, Z., Lee, B. W., & Crowder, D. W. (2021). Insect alarm pheromones in response to predators: Ecological trade-offs and molecular mechanisms. *Insect Biochemistry and Molecular Biology*, *128*, 103514.
14. Shorey, H. H. (2013). *Animal communication by pheromones*. Academic press.
15. Eisthen, H. L. (2002). Why are olfactory systems of different animals so similar?. *Brain, behavior and evolution*, *59*(5-6), 273-293.
16. Stengl, M. (2010). Pheromone transduction in moths. *Frontiers in cellular neuroscience*, *4*, 133.
17. Hildebrand, J. G., & Shepherd, G. M. (1997). Mechanisms of olfactory discrimination: converging evidence for common principles across phyla. *Annual review of neuroscience*, *20*(1), 595-631.
18. Sato, K., & Touhara\*, K. (2008). Insect olfaction: receptors, signal transduction, and behavior. *Chemosensory systems in mammals, fishes, and insects*, 203-220.
19. Williams, A. T., Verhulst, E. C., & Haverkamp, A. (2022). A unique sense of smell: development and evolution of a sexually dimorphic antennal lobe–a review. *Entomologia Experimentalis et Applicata*, *170*(4), 303-318.
20. Corey, E. A., & Ache, B. W. (2016). Comparative olfactory transduction. In *Chemosensory Transduction* (pp. 207-223). Academic Press.
21. Touhara, K., & Vosshall, L. B. (2009). Sensing odorants and pheromones with chemosensory receptors. *Annual review of physiology*, *71*(1), 307-332.
22. Breer, H., Raming, K., & Krieger, J. (1994). Signal recognition and transduction in olfactory neurons. *Biochimica et Biophysica Acta (BBA)-Molecular Cell Research*, *1224*(2), 277-287.
23. Fleischer, J., Pregitzer, P., Breer, H., & Krieger, J. (2018). Access to the odor world: olfactory receptors and their role for signal transduction in insects. *Cellular and Molecular Life Sciences*, *75*(3), 485-508.
24. Martin, J. P., & Hildebrand, J. G. (2010). Innate recognition of pheromone and food odors in moths: a common mechanism in the antennal lobe?. *Frontiers in Behavioral Neuroscience*, *4*, 159.
25. Hasan, W., Dileep Kumar, N. T., Khan, R. M., Hadimani, B. N., Behera, H. S., & Gireesha, D. Decoding the secrets of insect life: Pheromones, communication, and population dynamics.
26. Kocher, S. D., & Cocroft, R. B. (2019). Signals in insect social organization. In *Encyclopedia of animal behavior* (pp. 558-567). NY: Elsevier.
27. Buhl, C., & Rogers, S. (2016). Mechanisms underpinning aggregation and collective movement by insect groups. *Current Opinion in Insect Science*, *15*, 125-130.
28. Orlova, M., & Amsalem, E. (2019). Context matters: plasticity in response to pheromones regulating reproduction and collective behavior in social Hymenoptera. *Current Opinion in Insect Science*, *35*, 69-76.
29. Czaczkes, T. J., Grüter, C., & Ratnieks, F. L. (2015). Trail pheromones: an integrative view of their role in social insect colony organization. *Annual review of entomology*, *60*(1), 581-599.
30. Kaur, K., Chandel, M., Munikrishnappa, V. K. T., Kumar, P., Sahu, B. K., Ahamed, M., ... & Shanmugam, V. (2024). Ecofriendly agriculture pest control using pheromone packed programed nanovolcanoes framed by graphene oxide. *Clean Technologies and Environmental Policy*, 1-11.
31. Fincheira, P., Hoffmann, N., Tortella, G., Ruiz, A., Cornejo, P., Diez, M. C., ... & Rubilar, O. (2023). Eco-efficient systems based on nanocarriers for the controlled release of fertilizers and pesticides: Toward smart agriculture. *Nanomaterials*, *13*(13), 1978.
32. Sharifi, R., & Ryu, C. M. (2020). Formulation and agricultural application of bacterial volatile compounds. *Bacterial volatile compounds as mediators of airborne interactions*, 317-336.
33. Qadri, M., Short, S., Gast, K., Hernandez, J., & Wong, A. C. N. (2020). Microbiome innovation in agriculture: development of microbial based tools for insect pest management. *Frontiers in Sustainable Food Systems*, *4*, 547751.
34. Dong, Y., Jiang, T., Wu, T., Wang, W., Xie, Z., Yu, X., ... & Zhong, T. (2024). Enzyme-responsive controlled-release materials for food preservation and crop protection-A review. *International Journal of Biological Macromolecules*, *254*, 128051.
35. Hellmann, C., Greiner, A., & Vilcinskas, A. (2024). Design of polymer carriers for optimized pheromone release in sustainable insect control strategies. *Advanced Science*, *11*(9), 2304098.
36. Singh, A., Dhiman, N., Kar, A. K., Singh, D., Purohit, M. P., Ghosh, D., & Patnaik, S. (2020). Advances in controlled release pesticide formulations: Prospects to safer integrated pest management and sustainable agriculture. *Journal of hazardous materials*, *385*, 121525.
37. Singh, A., Dhiman, N., Kar, A. K., Singh, D., Purohit, M. P., Ghosh, D., & Patnaik, S. (2020). Advances in controlled release pesticide formulations: Prospects to safer integrated pest management and sustainable agriculture. *Journal of hazardous materials*, *385*, 121525.
38. Mamay, M., & Mutlu, Ç. (2019, November). Trend Biotechnological Management Methods Against Agricultural Pests: Mating Disruption, Mass Trapping and Attract & Kill. In *1st International Gobeklitepe Agriculture Congress* (pp. 511-517).
39. Trematerra, P. (1997). Integrated pest management of stored-product insects: practical utilization of pheromones. *Anzeiger für Schädlingskunde, Pflanzenschutz, Umweltschutz*, *70*, 41-44.
40. Morrison III, W. R., Scully, E. D., & Campbell, J. F. (2021). Towards developing areawide semiochemical‐mediated, behaviorally‐based integrated pest management programs for stored product insects. *Pest Management Science*, *77*(6), 2667-2682.
41. Cardé, R. T. (2021). Mating disruption with pheromones for control of moth pests in area-wide management programmes. In *Area-Wide Integrated Pest Management* (pp. 779-794). CRC Press.
42. Welter, S. C., Pickel, C., Millar, J., Cave, F., Van Steenwyk, R. A., & Dunley, J. (2005). Pheromone mating disruption offers selective management options for key pests. *California agriculture*, *59*(1).
43. El-Sayed, A. M., Suckling, D. M., Byers, J. A., Jang, E. B., & Wearing, C. H. (2009). Potential of “lure and kill” in long-term pest management and eradication of invasive species. *Journal of economic entomology*, *102*(3), 815-835.
44. Suckling, D. M., Stringer, L. D., Stephens, A. E., Woods, B., Williams, D. G., Baker, G., & El‐Sayed, A. M. (2014). From integrated pest management to integrated pest eradication: technologies and future needs. *Pest management science*, *70*(2), 179-189.
45. Savoldelli, S., & Trematerra, P. (2011). Mass-trapping, mating-disruption and attracticide methods for managing stored-product insects: Success stories and research needs. *Stewart Postharvest Review*, *7*(3), 1-8.
46. Martinez, B., Reaser, J. K., Dehgan, A., Zamft, B., Baisch, D., McCormick, C., ... & Selbe, S. (2020). Technology innovation: advancing capacities for the early detection of and rapid response to invasive species. *Biological Invasions*, *22*(1), 75-100.
47. Rajak, P., Ganguly, A., Adhikary, S., & Bhattacharya, S. (2024). Smart technology for mosquito control: Recent developments, challenges, and future prospects. *Acta Tropica*, 107348.
48. Yadav, A., Yadav, S., Shahi, N., Yadav, P. K., & Kumar, A. Chapter-13 Uses of Artificial Intelligence in The Agricultural Pest Management. *SMART AGRICULTURAL TECHNOLOGIES FOR SUSTAINABLE CROP PRODUCTION*.
49. Kariyanna, B., & Sowjanya, M. (2024). Unravelling the use of artificial intelligence in management of insect pests. *Smart Agricultural Technology*, 100517.
50. Adetunji, C. O., Olaniyan, O. T., Anani, O. A., Inobeme, A., Osemwegie, O. O., Hefft, D., & Akinbo, O. (2023). Artificial intelligence and automation for precision pest management. In *Sensing and Artificial Intelligence Solutions for Food Manufacturing* (pp. 49-70). CRC Press.
51. MacVeagh, M. R. (2022). *Maintenance Work: Climate Fiction and Process Biology*. Cornell University.
52. Kramer, R. M. (2014). *Molecular Signature Characterization of Select Agent Pathogen Progression* (Doctoral dissertation, University of Cincinnati).
53. Baynes-Rock, M. (2020). *Crocodile undone: The domestication of Australia’s Fauna*. Penn State Press.
54. Silverj, A., & Rota-Stabelli, O. (2019). Codon usage indicates that amphibians, reptiles and birds are major hosts for Zika and other arboviruses: implications for epidemiology and surveillance. In *8th Congress of the Italian Society for Evolutionary Biology, Padua, 1-4 September 2019* (p. 7). IT.
55. Abston, S., & Aly, S. Adams, Shelby; Anaya, Berenice; Arnold, Jessica; Lowery, Danielle; Herricks, Sarah;" Risky Business?.
56. Huang, K., & Rota-Stabelli, O. (2019). Highly-resolved strain-level population dynamics of Wolbachia from large-scale metagenomes. In *Evoluzione 2019: 8th Congress of the Italian Society for Evolutionary Biology, Padua, 1-4 September 2019* (p. 56). IT.
57. MacLeod, L. R., Lopez, C., Etuk, A., & Wickramasinghe, P. (2024). Richard E. Peter 15th Annual Biology Conference (2024). *Undergraduate Research in Natural and Clinical Science and Technology Journal*, *8*, A1-A60.
58. Koul, O. (2016). Antifeedant phytochemicals in insect management (so close yet so far). In *Ecofriendly Pest Management for Food Security* (pp. 525-544). Academic Press.