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An Overview of Insect Semiochemical Detection

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ABSTRACT

Insects and other organisms communicate through semiochemicals, such as pheromones and allelochemicals, *etc*. These chemicals control some of the important functions needed by insects to survive which include mating, aggregation, foraging, defense and oviposition. Precise identification and analysis of these chemicals are essential in ecological research and in sustainable pest-management devices. This paper presents the primary methods of insect semiochemical detection, which are pheromones. It encompasses few older methods such as gas chromatography and mass spectrometry and electroantennography. Newer sensor methods include electrochemical, piezoelectric, optical, biosensors and cantilever nanosensors. The short-term uses of these technologies in agriculture are also mentioned in the review, as they are primarily applied in integrated pest management, monitoring population, and controlling pests in an environment-friendly manner.

INTRODUCTION

Insects rely mainly on chemical signaling as a form of communication and this helps them to survive in a complex ecological landscape. Semiochemicals produced by insects are broadly classified into two segments *i.e.* pheromones and allelochemicals, which have distinct ecological functions:

Pheromones: Chemical signals that regulate a wide range of behaviour in between organisms of the same species (Intraspecific interactions) (Yew and Chung, 2015). Pheromones cause a specific reaction, such as evoking a certain behaviour (immediate response to the behaviour of the receiver) that is referred to as a releaser pheromone or a developmental process (physiological responses of the receiver) that is called a primer pheromone. Release pheromones stimulate an immediate and reversible behavioural response, which remains for a short period. For example, sex pheromone(mating), alarm pheromone (defence, *i.e.,* warn conspecific species), Trail pheromone, aggregation pheromone.

Allelochemicals: Chemicals that mediate interspecific interactions (in between two different species) (Yew and Chung, 2015).These are subdivided into:

- *Kairomones*: Benefit the receiver, such as plant volatiles that attract herbivorous insects.
- *Allomones*: Benefit the emitter, like defensive secretions deterring predators.
- *Synomones*: Benefit both emitter and receiver, such as floral scents attracting pollinators.
- *Apneomone*: pheromone released from a non-living source (like decaying matter) that benefits a receiver such as a predator or parasite, while harming the organism linked to that source.

Use of pheromone-based system of pest control is highly considerable due to its less environmental impact flora and fauna as it reduces the three R's (Resistance, Resurgence and Residue). Pheromones are highly specific to a pest species, whereas broad-spectrum synthetic pesticides affect and kill all other similar species and organisms (natural enemies such as Predators and Predators). Moreover, pheromones break down quickly in the field, which reduces the ecological ramifications in a long-term context. As a result, pheromone technologies have found a place in sustainable agriculture, integrated pest management, and conservation biology. Modern-day practices of crop protection have been sharpened with the use of sex and aggregation pheromones in their application in pest management practices. In mass-trapping systems, synthetic pheromones are used that allow large groups of target pests to be attracted and trapped, reducing the general levels of population. In mating-disruption systems, the habitat is flooded with unnatural pheromonal signals that disrupt conspecific mate-locating, finally decreasing the likelihood of achieving successful reproduction. Moreover, it is possible to note that monitoring traps based on pheromones provide real-time diagnostics of pest populations, which also makes it possible to apply special and timely intervention methods. All these measures contribute to the achievement of an increased pest-control efficacy, reduce the overdependence on the use of chemical pesticides and help develop the model solution of labor-saving practices in agriculture by reducing anthropogenic effects on the environment.The effective use of these strategies, however, relies on the sensitivity to measure insect semiochemicals in complex environmental matrices accurately, identify and detect these semiochemicals (Abdallah, 2024).

Pheromone molecules and its chemistry

The chemical nature of insect pheromones is remarkably diverse, reflecting the evolutionary process that drives species-specific communication. The pheromone molecules can be simple hydrocarbons or complex, multifunctional molecules, such as terpenes and heterocyclic compounds and may have functional groups added to them, such as double bonds or epoxide groups, to make them more specific. It is this diversity that enables insects to use and utilize highly species-specific mixtures, in many cases with exact stereochemistry and proportions of components, to coordinate communication and mating activities (Brezolin *et al.,* 2018).

For example:

Stink Bugs (Pentatomidae) produce a variety of aldehydes, esters, and ketones that function both as defensive compounds and pheromones. For example, trans-2-hexenal and methyl (E,E)-2,4-decadienoate are common components of their chemical arsenal, serving to repel predators and mediate intraspecific communication.

Lepidopteran Pheromones: These are among the most extensively studied due to their applicability and diversity. They are categorized into:

- *Type I*: Linear aliphatic compounds (C10-C18) with alcohols, acetates, or aldehydes as functional groups. These are usually volatile compounds which are applied in long-distance attractions.
- *Type II:* Long chain hydrocarbons (C17-C23) that are usually epoxidized or otherwise modified and are not very volatile and can be involved in close-range communication.

Stereochemistry of pheromones plays a major role in the biological activity of these compounds. Enantiomers (mirror-image isomers) can also exhibit strikingly different insect behavior, as one enantiomer induces attraction and is inactive or even repulsive. The exact combination and proportion of pheromone constituents are also a decisive factor; minor variations will diminish its effectiveness. Pheromone-based pest management can be successfully initiated due to its chemical accuracy.

Methods for pheromone extraction

Pheromones are obtained after subjecting insects, especially to scrutiny. This would require the most appropriate methods based on the physical-chemical characteristics of the pheromones; volatility, polarity, stability and the production of the pheromones. Pheromones are deposited from glandular secretions on the cuticle and are released into the environment as airborne volatile compounds. (Rizvi *et al.,* 2021; Brezolin *et al.,* 2018)

- **Aeration (Volatile Collection)**: This is a non-invasive method that keeps insects in an airtight enclosure that has fresh air. The volatile compounds are held on the adsorbents which are solid e.g. Trongapak Q or Tenax. Aeration is also suitable, especially in permanently collected sampling since it allows the pheromone to settle as it naturally builds up.
- **Solvent Extraction:** Solvent extraction occurs when the pheromones are absent as volatile compound or unable to become volatile as glands release them. Pheromones in tissues of interest could be solubilized in organic solvents such as hexane and dichloromethane. Although it produces concentrated extracts, the process is wide-ranging and mostly scoops out undesirable elements that require additional cleaning efforts.
- **Solid -Phase Microextraction (SPME):** SPME is another solventless technique where volatile and semi volatile interruptions are absorbed onto a fiber covered with a polymer in liquid or air. One then inserts the fiber into the thermal desorber of a gas chromatograph. It is a highly sensitive, quick, and needs humble amounts of samples, which makes it applicable to both laboratory and field studies.

Together, these methods of analysis form the basic scheme of semiochemical studies. As they help to discover, characterize and quantify pheromones, they also provide the necessary tools to create pheromone-based pest management approaches which are both capable and environmentally friendly.

Pheromone identification, quantification and confirmation techniques

Analysis to identify and determine the insect pheromones requires advanced techniques capable of resolving complex chemical mixtures. The analysis provides a reasonable solution to intricate mixtures of chemicals and gives a clear structure determination of molecules (Brezolin *et al.*, 2018).

- **Gas Chromatography (GC):** GC is the separation of volatile organic compounds, using their volatilities and the characteristics of the stationary phase. In addition to the flame ionization detection (FID), GC provides very sensitive and reproducible quantitative data. It is based on these data that the composition and concentration of pheromone can be comprehended.

- **Gas Chromatography Mass spectrometry techniques (GC-MS)**: GC-MS combines the separation capability of gas chromatography and the structure identification capability of mass spectrometry. Mass spectra provide an accurate molecular weight, unique patterns of fragments and hence enable identification of the unknown ephemeral constituents of the pheromones even when trace amounts are present. Such an approach is needed to define the structure of a pheromone and identify it.

- **Electroantennography (EAG):** EAG is a biological detector of physiologically active compounds on insect antennae and is used to measure the electrical response of the antennae to certain odorants. This technique in conjunction with GC (GC-EAD) allows researchers to directly correlate chromatographic peaks with the responses of antennas, which is important information in critical detailing which compounds may act as biologically relevant pheromones. (Roelofs, 1984).

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Semiochemical detecting sensors

However, more recent developments in sensor technology led to the development of chemical detectors that provide rapid, sensitive and portable monitoring of insect semiochemicals in addition to the conventional analysis methods. These help in real-time detection at both the lab and field levels (Brezolin *et al.*, 2018). Consequently, these are extended for the application of pheromone-based pest management and ecological studies.

- **Electrochemical sensors:** Electrochemical sensors are tools used to measure electrical properties (current, potential, or conductivity) that vary when a semiochemical bonds with the sensor surface. They are typically fabricated with metal-oxide semiconductors including tin oxide and zinc oxide or conducting polymers included in the category of polypyrrole. Their benefits are affordability, simple miniaturization and the capability to offer real-time monitoring.

- **Piezoelectric Sensors:** Scanners using piezoelectric microbalance, such as the quartz crystal microbalance (QCM) and a surface acoustic wave sensor (SAW) can detect variations in the frequency of oscillation when volatile organic compounds adsorb on the sensor. Due to their high sensitivity, these sensors are sensitive and can detect traces of pheromones even at a very small mass change.

- **Optical Sensors:** Optical sensors are used in detecting changes in the refractive index of the surface of optical sensors (surface plasmon resonance (SPR) device) when the semiochemicals adsorb onto pre-attached recognition molecules. It is a label-free, high-sensitivity, real-time technique that can differentiate between distinct molecules.

Beyond individual sensor platforms, sensor arrays (also known as electronic noses) with several sensing devices can be used to recreate insect olfactory discrimination between multiple odor mixtures. These arrays promise significant usage in a variety of applications such as pest population monitoring, food quality and environmental surveillance.

Biosensors

Biosensors combine biological recognition elements with physical transducers to enable highly selective and sensitive detection of insect semiochemicals. By incorporating components derived from insect olfactory systems, these devices exploit evolutionary adaptations for chemical discrimination, achieving sensitivity levels that often surpass conventional sensor technologies (Bohbot *et al.,* 2020).

- **Olfactory Organs and Olfactory-binding proteins (OBPs):** Insects consists of OBPs and olfactory receptors which can be mobilised on sensory device surface which provides exceptional selectivity for specific pheromones or plant volatiles. These biosensorsare capable of detecting the target chemical compounds even at low concentrations.

- **Cell-Based Biosensors:** This technology uses genetically modified cells or engineered cells expressing insect odorant binding receptors, which generate measurable electrical or optical signals in response to semiochemical binding. These technologies help in high-throughput screening capacity, real-time detection.

Biosensors together offer response times, flexibility and durability in the field. They can become a powerful tool for pest control, environmental bioinformatics and ecological research due to their imitation of natural olfactory functions, thus overcoming the gap between laboratory research and practical field work.

Cantilever Nanosensors

Cantilever Nanosensors Semiochemicals in insect are also discerned with the cantilever based nanosensors which is a state of art technology developed out of atomic force microscopy (AFM). These machines can detect molecular interaction with high-resolution accuracy (Dias *et al.,* 2024).

a. **Functionalization:** Cantilevers can be functionalized with polymers, peptides or insect olfactory membranes, which are highly specific to binding pheromones. As the target molecules adsorb to the surface, the resonance frequency of the cantilever is altered, or it is bent and these modifications are easily measured in sub-nanometers.

b. **Integration of Micro Electromechanical Systems (MEMS):** MEMS technology has recently made miniaturized multi-array cantilever arrays through miniature and multi-channel technologies achievable. These highly efficient but small systems can be sold to field locations and monitor several semiochemicals at a time, which makes them an ideal tool for real-time on-valley measurements.

c. **Sensitivity:** Cantilever-type nanosensors have the capability of detecting limits in the femtogram regime, which is extremely superior to any other conventional technology. They lack all labels, are fast in acting and amplify large samples, which makes them powerful tools of pests control, ecological research and lab work.

CONCLUSION

Chemical communication in insects constitutes a complex system underlying their existence, reproduction and ecological interactions. While pesticides of conventional type can be both species-specific and effective by simply harnessing this communication through pheromone-based control of pests we eliminate the ecological damage they might cause. This helps to sustain and increase biodiversity on our planet. As it stands, insect semiochemicals should eventually become detectable and monitorable online through the latest sensor and biosensing technologies including nano-scale devices that integrate materials with biological components.

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