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Original Article

Harnessing semiochemicals in pest control: A sustainable approach to ipm

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1. INTRODUCTION

Semiochemicals are signaling chemicals that facilitate communication between living organisms, leading to behavioural changes in the receiving organism (Pringal Upadhyay *et al.,* 2024). They are typically released by one individual and detected by another. In invertebrates, particularly insects, olfaction (sense of smell) is the primary method for sensing these signals in their environment. Insects are attracted to plants or other hosts by detecting specific semiochemicals or a combination of them. On the other hand, insects avoid unsuitable hosts when they identify specific semiochemicals associated with non-host species. Semiochemicals play a significant role in integrated pest management (IPM) as they offer the potential for non-toxic solutions to control pests. These chemicals can be used to lure insects into bait traps for monitoring and managing pest populations. Additionally, semiochemicals that repel pests or attract their natural predators can help maintain pest populations at manageable levels.

Semiochemicals can serve multiple functions depending on their context. For example, herbivore-induced plant volatiles may repel herbivorous insects while simultaneously attracting their predators or parasitoids. The term "infochemical" (Mishra et al., 2022) has been proposed to describe these chemicals, particularly when they are involved in complex interactions across multiple trophic levels. Insects face strong evolutionary pressures to detect food sources accurately since their survival and reproduction depend on it. Even generalist insects have developed mechanisms to avoid landing on non-host plants. As public demand grows for environmentally friendly pest control methods, the use of semiochemicals is gaining traction. Unlike toxic insecticides, semiochemicals are typically species-specific, used in minimal quantities, and pose minimal risks to vertebrates and beneficial insects.

2. TYPES OF SEMIOCHEMICALS

There are two main categories of semiochemicals:

Pheromones and **Allelochemicals** (El-Ghany *et al.,* 2019).

Pheromones work within the same species and are used for communication purposes, such as signalling mating, danger, aggregation, or territory marking.

Allelochemicals function between different species and can be further classified based on their effects: kairomones benefit the receiver, allomones benefit the emitter, and synomones benefit both parties.

2.1. PHEROMONES

The word pheromones comes from the Greek word ***pherin*** which means "to carry" or "to bear" and ***horman*** which means "to excite" or "to stimulate"

Chemistry of Pheromones: Pheromones are composed of different chemical structures, including aldehydes, esters, amines, acids, ketones, phenols, and alcohols. The specific arrangement and the number of carbon atoms in a pheromone molecule determine its function and effectiveness. For example, they may range from one carbon atom (e.g., formic acid) to much larger molecules like **heptatriacontadiene**. Double bonds in these molecules create isomers (e.g., "E" and "Z" forms), and the arrangement of these isomers affects how insects respond to the pheromone.

Synthesis of Pheromones: The synthesis process involves creating pheromones with accurate structures, matching those naturally occurring in insects. This includes forming the correct carbon skeleton, ensuring functional groups are added correctly, and maintaining the stereo-chemistry (3D arrangement) to match the natural isomeric forms. Specialized techniques and resources like "Pherobase" provide step-by-step synthesis pathways for different pheromones. The synthesized pheromones are tested using advanced techniques like Electroantennogram (EAG) and Gas Chromatography-Mass Spectrometry (GC-MS) to verify their chemical and biological functionality.

Types of Pheromones: Pheromones are classified into two main categories

Releaser pheromones and **Primer pheromones** (Abd El-Ghany and N. M (2020).

2.1.1. Releaser pheromones:

Releaser pheromones: These cause immediate behavioural responses in the receiver. Examples include Sex Pheromones, Trail Pheromones, Aggregation Pheromones, Alarm Pheromones, Anti-aggregation Pheromones (Poornakala *et al.,* 2023).

I. **Sex Pheromones**: These are chemical substances released by one sex (usually females) to attract individuals of the opposite sex (usually males) for mating purposes. They are typically volatile and can travel long distances through the air.

Functions

- **Mate Attraction**: The primary function of sex pheromones is to attract potential mates. Females often release these pheromones into the environment to signal their readiness to mate.
- **Species Specificity**: Sex pheromones are generally species-specific, meaning that they only attract individuals of the same species. This specificity helps prevent interbreeding between different species.
- **Sexual Selection**: In many cases, the ability to detect and respond to sex pheromones is linked to reproductive success, influencing sexual selection and mating behaviors.

Mechanism of Action

- **Detection**: Male insects detect sex pheromones using specialized sensory receptors on their antennae. This olfactory response triggers a series of behavioural changes, such as increased movement toward the source of the pheromone.
- **Response**: Upon detecting the pheromone, males may exhibit behaviours such as flight toward the female, courtship displays, or other mating rituals.

Examples of Sex Pheromones

- **Moths**: Female moths often release sex pheromones that can attract males from several kilometers away. For instance, the *Helicoverpa armigera* (cotton bollworm) female releases a blend of **Z-11-hexadecenal** and **Z-9-hexadecenal**, which are highly attractive to males.
- **Butterflies**: In many butterfly species, males can detect the pheromones released by females, prompting them to engage in courtship behaviour.
- **Beetles**: Certain species of beetles also use sex pheromones to facilitate mating. For example, the **Japanese beetle** (*Popillia japonica*) releases pheromones that attract males for mating.
- **Fruit Flies**: In fruit flies, the male releases specific pheromones that attract females. The interaction between male and female pheromones is crucial for reproductive success.

II. **Trail Pheromones**: These are volatile chemicals secreted by insects that create a pathway or "trail" for other members of the same species to follow as shown in Fig 1. They are primarily used to guide individuals to food sources, nesting sites, or other important locations.

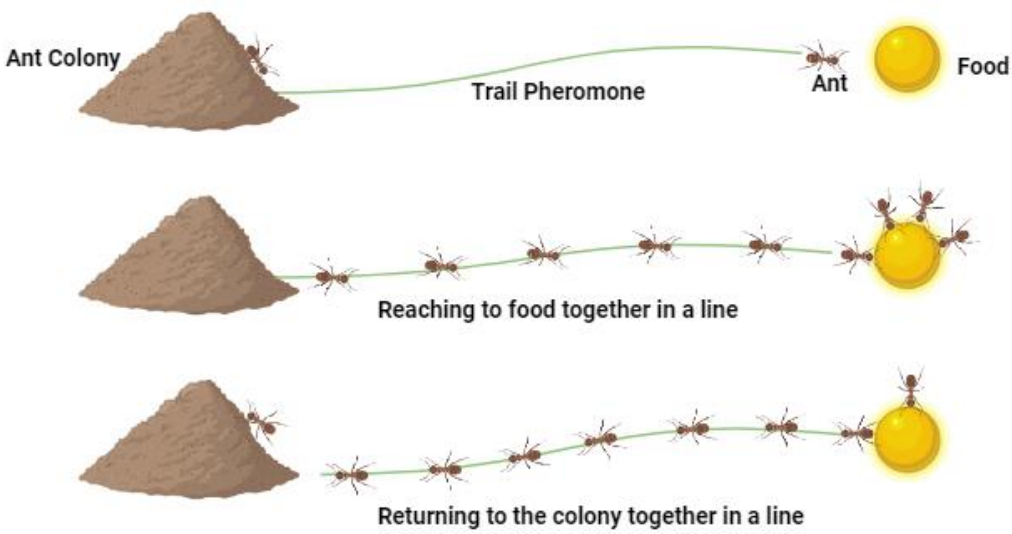

Fig 1 Action of Trail Pheromone

Functions

- **Navigation**: Trail pheromones help insects find their way back to food sources or the nest. By following the pheromone trail, they can navigate effectively in their environment.
- **Recruitment**: When an insect discovers a food source, it can deposit trail pheromones to recruit other colony members. This leads to a rapid and efficient gathering of resources.
- **Territory Marking**: In some cases, trail pheromones may also be used to mark territorial boundaries or communicate the status of a resource.

Mechanism of Action

- **Production**: Trail pheromones are typically secreted from specialized glands in the insect's body. For example, ants produce trail pheromones from their mandibular glands or poison glands.
- **Detection**: Insects detect these pheromones using olfactory receptors on their antennae. The concentration of the pheromone indicates the strength of the trail; a stronger trail usually means a more active route or a recently visited food source.
- **Behavioural Response**: When an insect encounters a pheromone trail, it may follow it by increasing its movement speed and direction towards the source of the pheromone. This behaviour can be reinforced by additional pheromone deposits from other individuals.

Examples of Trail Pheromones

- **Ants**: Many ant species, such as **Argentine ants** (*Linepithema humile*), utilize trail pheromones extensively. When foraging, an ant will leave a pheromone trail from the food source back to the nest, allowing other ants to follow the scent and find the food.
- **Termites**: Some termite species use trail pheromones to lead colony members to wood sources or their nesting sites, facilitating efficient resource gathering.
- **Bees**: Certain species of bees may use trail pheromones to communicate the location of food sources to their nest mates, though they primarily rely on different foraging signals.

III. **Aggregation Pheromones**: These are chemicals released by insects that promote the gathering of individuals of the same species in a particular area. They signal the presence of food, breeding sites, or suitable habitats, encouraging others to join.

Functions

- **Resource Location**: Aggregation pheromones help insects find and exploit food sources. When one insect discovers a resource, it can release these pheromones to attract others.
- **Mating Opportunities**: In some species, aggregation pheromones can signal suitable locations for mating, bringing individuals together to enhance reproductive success.
- **Protection**: By clustering together, insects may benefit from increased protection against predators or environmental hazards.

Mechanism of Action

- **Production**: Aggregation pheromones are typically secreted from specialized glands in the insect's body. For example, many beetles release these pheromones from their **exocrine glands**.
- **Detection**: Insects detect aggregation pheromones using olfactory receptors on their antennae. The concentration and type of pheromone indicate whether the area is favourable for gathering.
- **Behavioural Response**: When an insect encounters aggregation pheromones, it is likely to exhibit behaviours such as increased movement toward the source, ultimately leading to clustering with conspecifics.

Examples of Aggregation Pheromones

- **Bark Beetles**: One of the most well-studied examples involves bark beetles, which use aggregation pheromones to attract mates and other beetles to host trees. Species like *Dendroctonus ponderosae* (mountain pine beetle) release a blend of terpenoids that signals suitable trees for colonization, often leading to mass attacks that can kill the tree.
- **Ants**: Certain ant species release aggregation pheromones to recruit nestmates to food sources or new nesting sites. This behaviour enhances foraging efficiency and colony growth.
- **Fruit Flies**: Some fruit flies, such as *Bactrocera dorsalis* (oriental fruit fly), use aggregation pheromones to attract mates and establish mating sites on host fruits.

IV. **Alarm Pheromones**: These are volatile chemical compounds secreted by insects that signal alarm or danger to other members of the same species. They prompt immediate defensive or evasive behaviours.

Functions

- **Threat Detection**: Alarm pheromones are used to indicate the presence of predators or other dangers in the environment. When an insect perceives a threat, it releases these pheromones to alert others.
- **Coordinated Defense**: The release of alarm pheromones helps to coordinate group responses, leading to collective behaviours such as fleeing, aggression, or forming defensive formations.
- **Communication of Severity**: The composition and concentration of alarm pheromones can convey information about the level of threat, influencing the intensity of the group's response.

Mechanism of Action

- **Production**: Alarm pheromones are produced in specialized glands, such as the mandibular glands in many social insects. They can vary in composition depending on the species and the type of threat.
- **Detection**: Insects detect alarm pheromones using olfactory receptors on their antennae. This recognition triggers immediate behavioural changes in other individuals.

- **Behavioural Response**: Upon detecting alarm pheromones, insects may exhibit behaviours such as fleeing the area, becoming more aggressive, or clustering together for protection.

Examples of Alarm Pheromones

- **Honeybees**: Honeybees release alarm pheromones (e.g., **isopentyl acetate**) when they perceive a threat to the colony, such as an intruder. This pheromone alerts other bees, leading them to become defensive and attack the threat.
- **Ants**: Many ant species, such as Carpenter ants, use alarm pheromones to warn colony members of approaching predators. The pheromone releases can prompt aggressive behaviour toward intruders or encourage the colony to evacuate.
- **Termites**: Termites also utilize alarm pheromones to communicate danger, often triggering defensive behaviours among colony members in response to threats from predators or disturbances.

V. **Anti-aggregation pheromone**: It is a chemical signal that insects release to discourage others of the same species from gathering in a specific area. Unlike aggregation pheromones, which attract individuals to a location, anti-aggregation pheromones indicate that the site is already occupied or unsuitable for additional individuals, thus helping to prevent overcrowding.

Functions

- **Prevent Overcrowding**: Anti-aggregation pheromones signal to conspecifics that a location is already occupied, reducing competition for food, nesting sites, or mating opportunities.
- **Resource Management**: By discouraging additional individuals from gathering, these pheromones help ensure that available resources are not overexploited or depleted.
- **Enhancing Survival**: By minimizing competition and overcrowding, anti-aggregation pheromones contribute to the overall health and survival of the species in an ecosystem.

Mechanism of Action

When insects discover a food source, nesting site, or mating area, they may release anti-aggregation pheromones to signal that the location is already occupied. This communication helps to avoid competition and ensures that resources are not overused or depleted. For example, bark beetles utilize anti-aggregation pheromones; after an initial population invades a tree and reaches a certain density, they release signals to prevent additional beetles from attacking the same tree, thereby reducing competition for resources.

Examples of Anti-aggregation Pheromones

- **Verbenone** is a well-known antiaggregation pheromone used by various bark beetle species. It signals to other beetles that the tree is already infested and not suitable for further colonization.
- **Ipsdienol**, another example, is used by beetles in the genus *Ips* to limit further attack once they have occupied a tree.

- **Methyl Jasmonate**: Some studies suggest that this compound, although primarily known for its role in plant defense, may also function as an antiaggregation pheromone in certain insect species by signaling resource depletion.

2.1.2. **Primer pheromones:** These have long-term physiological effects on the receiver, often influencing developmental processes. A well-known example is caste determination in social insects such as bees, wasps, and ants, where pheromones play a critical role in the development of specific roles within the colony.

Applications of Pheromones in Integrated Pest Management (IPM):

a. **Monitoring:**

Various types of synthetic pheromones, such as sex pheromones, trail pheromones, aggregation pheromones, and alarm pheromones, are widely used in pest monitoring strategies. Sex pheromones help track insect populations by attracting specific pests like moths, while trail pheromones are effective in monitoring social insects like ants. Aggregation pheromones are used to lure and group pests, enabling better monitoring of target species. Alarm pheromones, on the other hand, induce flight responses, allowing traps to capture pests effectively by simulating a threat. Together, these pheromones provide a comprehensive approach to pest population surveillance and control.

b. **Mass Trapping:** (Table 1)

Sex Pheromones: Synthetic sex pheromones attract male pests, such as moths, into traps, preventing them from mating and thereby reducing pest populations.

Trail Pheromones: Traps that mimic the trail-following behaviour of social insects, like ants, are used to monitor and control their populations effectively in infested areas.

Mass Trapping for Key Pests:

- *Rhynchophorus ferrugineus* (red palm weevil) and *Cosmopolites sordidus* (banana weevil) are controlled through pheromone traps, capturing large numbers of these pests.
- In crops such as rice and sugarcane, pheromone traps are deployed to manage pests like *Scirpophaga incertulas* (yellow stem borer), helping to protect crops from damage and yield loss.

Table 1 Insects and Pheromones used for mass Trapping

Species	Compound
Anomala vitis Fabricius *A. dubia* Scopoli	(E)-2-Nonen-1-ol
Anthonomus rubi Herbst.	(Z)-2-(3,3-Dimethyl)-cyclohexylidene ethanol
Bactrocera oleae (Gmelin)	Yellow triangular cardboard Ecotrap
Cameraria ohridella Deschka	(E,Z)-8,10-Tetradecadienal
Chilo infuscatellus Snell	(Z)-11-Hexadecen-1-ol

c. **Common Parapheromones:**

Parapheromones, which are compounds that mimic natural pheromones, are frequently used in pest control and monitoring strategies. Here are some of the key parapheromones used in IPM:

- **Methyl Eugenol**: Derived from plants like basil, methyl eugenol is a powerful attractant for male *Bactrocera* fruit flies, including the oriental fruit fly (*Bactrocera dorsalis*). It is used in traps to monitor and control fruit fly populations, particularly in orchard and horticultural settings.
- **Cuelure and Trimedlure**: These parapheromones, also plant-derived, are used to attract and trap other fruit fly species. They are particularly effective in citrus orchards and melon fields, helping to manage fruit fly populations in large-scale agricultural operations.

These parapheromones are essential for biodiversity studies, population monitoring, and quarantine programs, allowing experts to detect and assess the abundance of pest species in a given region. They play a significant role in safeguarding crop health and minimizing pest-related damages.

d. **Mating Disruption:**

This involves releasing high concentrations of synthetic sex pheromones into a crop field to confuse male insects and prevent them from locating females. When the air is saturated with these synthetic pheromones, the males are unable to follow the natural scent trails emitted by females, leading to reduced mating success.

- Mating disruption is primarily used for managing pests like **codling moths** in apple orchards, **grapevine moths**, and **peach moths**, as these pests rely heavily on pheromones for mating.
- In rice fields, mating disruption has been successfully applied for pests such as the **rice stem borer**, reducing their populations significantly.
- This method is also effective for other crops like cotton, where it targets pests like the **pink bollworm**, helping minimize damage. (Bakthatvatsalam *et al.,* 2022)

2.2. **ALLELOCHEMICALS**

Allelochemicals are a subclass of semiochemicals that facilitate chemical communication between different species, transmitting interspecies signals. These compounds are produced by one species and interpreted by another, with various outcomes depending on the nature of the interaction between the signaler and the receiver (Fig 1). They can be categorized into five distinct types based on the impact on both the emitter and the receiver, as detailed in the following:

2.2.1. **Allomones:** Derived from the Greek words "allos" (other) and "hormone" (excite), allomones are chemicals released by one organism that provoke a reaction in another species, benefiting the emitter. For example, many insects and plants produce allomones as a defensive strategy, deterring predators. A notable case is the production of nicotine by tobacco plants, which acts as a toxic deterrent against herbivorous insects. Another fascinating example involves bolas spiders, which deceive and capture male moths by imitating moth pheromones.

2.2.2. **Kairomones:** Kairomones, originating from the Greek word "***kairos***" (opportunity), are chemicals emitted by one species that elicit a response from another species, benefitting the recipient. An example is the attraction of predatory beetles to the aggregation pheromones produced by their prey, the bark beetles. Interestingly, kairomones can also function as allomones or pheromones depending on the context, as in the case of bolas spiders, which lure male moths by releasing pheromone-like compounds.

2.2.3. **Synomones:** Synomones are chemicals that provide mutual benefits to both the emitter and receiver. A classic example is the scent produced by flowers to attract pollinators. Additionally, when plants are attacked by herbivores, they may release volatiles that attract natural enemies of the pests, thus serving both the plant and the predator. Synomones are also crucial in mating communication, helping species avoid competition by fine-tuning their olfactory signals. In termites, hydroquinone acts as both a pheromone and synomone, depending on whether it is detected by members of the same species or different species foraging in the same area.

2.2.4. **Antimones:** Antimones are compounds that have negative effects on both the emitting organism and the recipient. When encountered by another species, these chemicals trigger a repellent reaction that is disadvantageous to both parties involved.

2.2.5. **Apneumones:** Apneumones, derived from the Greek word "***a-pneum***" meaning "without breath," are chemicals emitted by non-living materials that induce a beneficial behavioral or physiological response in one organism but may negatively affect other species interacting with the same material. A rare example includes hexanal and 2-methyl-2-butanol, which are released from rabbit feces and attract sandfly females for egg-laying.

These categories of allelochemicals illustrate the complexity of interspecies chemical communication, with effects ranging from mutual benefit to detrimental impacts for the species involved Abd El-Ghany and N.M (2020).

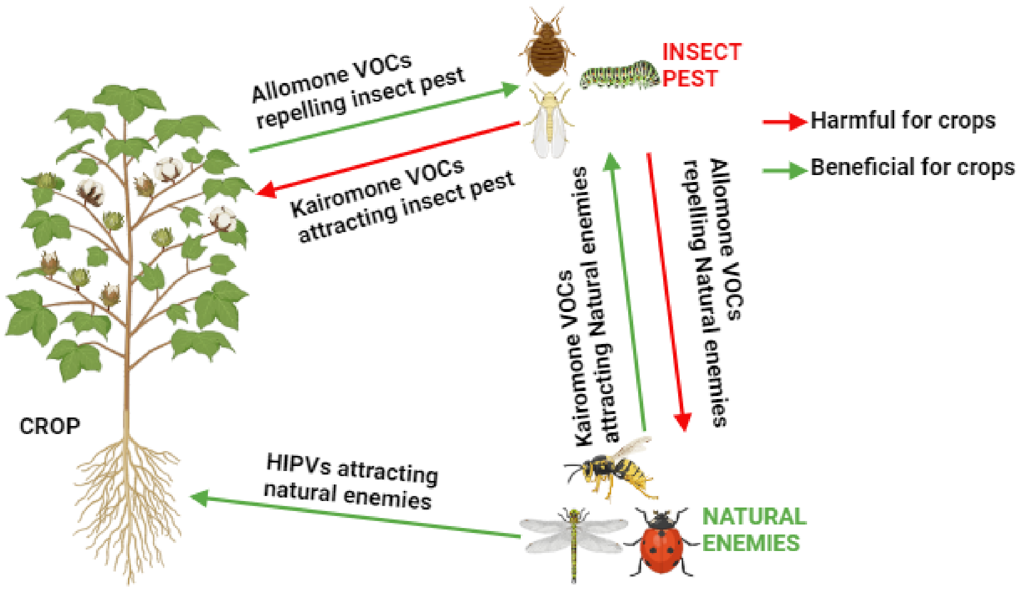

Fig 2 Action Mechanism of Allelochemicals

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