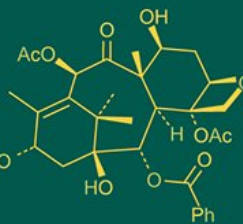
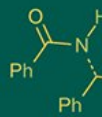


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(8): 1881-1891
www.biochemjournal.com
Received: 07-06-2026
Accepted: 10-07-2026

PB Toradmal

M.Sc. (Agri.) Student,
Department of Entomology,
Government College of
Agriculture, Dhule, Mahatma
Phule Krishi Vidyapeeth,
Rahuri, Maharashtra, India

AS Mahale

I/C Professor, Government
College of Agriculture, Dhule,
Mahatma Phule Krishi
Vidyapeeth, Rahuri,
Ahilyanagar, Maharashtra,
India

KS Kolhe

M.Sc. (Agri.) Student,
Department of Entomology,
Government College of
Agriculture, Dhule, Mahatma
Phule Krishi Vidyapeeth,
Rahuri, Maharashtra, India

AK Mali

Ex. Assistant Professor of
Entomology, Government
College of Agriculture, Dhule,
Mahatma Phule Krishi
Vidyapeeth, Rahuri,
Maharashtra, India

PS Magdum

M.Sc. (Agri.) Student,
Department of Entomology,
Government College of
Agriculture, Dhule, Mahatma
Phule Krishi Vidyapeeth,
Rahuri, Maharashtra, India

Corresponding Author:**PB Toradmal**

M.Sc. (Agri.) Student,
Department of Entomology,
Government College of
Agriculture, Dhule, Mahatma
Phule Krishi Vidyapeeth,
Rahuri, Maharashtra, India

Use of semiochemicals in integrated pest management

PB Toradmal, AS Mahale, KS Kolhe, AK Mali and PS Magdum

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i8Su.9689>

Abstract

Semiochemicals are chemical signals that regulate interactions among insects and between insects and plants and have significant potential in sustainable insect pest management. This review examines the role of pheromones and allelochemicals and their applications in integrated pest management (IPM), including pest monitoring, mass trapping, mating disruption, push-pull strategies and lure-and-infect techniques. Recent advances such as controlled-release formulations, automated monitoring systems and integration with remote sensing have improved the precision and efficiency of semiochemical-based pest management. Compared with conventional chemical pesticide these approaches offer species-specific pest suppression, compatibility with biological control and reduced dependence on broad-spectrum insecticides. Overall, semiochemicals represent an important component of modern Integrated pest management and provide promising opportunities for environmentally sustainable and climate-resilient crop protection.

Keywords: Semiochemicals, Pheromone, Allelochemicals, Integrated pest management.

Introduction

Semiochemicals are chemical compounds or mixtures released by one organism that elicit behavioural or physiological responses in members of the same species or different species (Nordlund and Lewis, 1976) [73]. The adverse effect of pesticides on soil, water, humans, animals and ultimately the environment diverted the attention of the scientific community to develop an ecofriendly approach for managing the devastating crop pests (Manda *et al.*, 2020) [60]. Semiochemicals can use in integrated pest management (IPM). These compounds play a crucial role in insect communication by mediating both insect-insect and plant-insect interactions. Chemical signals exchanged among insects, host plants and their environment are essential for insect survival enabling them to modify their behaviour in response to environmental cues. These cues known as semiochemicals influence physiological and behavioural responses within a species as well as between different species. Host plant volatiles serve as important semiochemical cues by helping insects locate essential resources including food, mates, oviposition sites and shelter (Prokopy *et al.*, 1984; Witzgall *et al.*, 2010) [80, 112]. The term semiochemical originates from the Greek word "semeon" (Firn, 2011) [38]. Depending on the nature of the interactions, chemical communication between organisms can be broadly classified into two basic types: intraspecific and interspecific communication. Pheromones and allelochemicals are examples of intraspecific and interspecific chemical communication respectively (Nordlund *et al.*, 1981) [74]. Pheromones have evolved as chemical signals that facilitate communication related to sexual attraction, alarm, aggregation, and territorial marking. In contrast, allelochemicals are classified based on who benefits from the interaction: kairomones benefit the receiver, allomones benefit the emitter, and synomones provide advantages to both organisms. The interactions between plant semiochemicals and insect pheromones differ in their modes of action, and their combined use can improve the effectiveness of pest management strategies (Bakthavatsalam and Subaharan, 2016) [11]. Furthermore, semiochemicals are categorized into several functional groups according to the type of information they convey and the ecological relationship between the emitting organism and the receiving organism during chemical communication (Vilela and Della Lucia, 2001) [109]. Semiochemicals play a crucial role in regulating insect behavior and are involved primarily in insect-insect and plant-insect interactions (Abd El Ghany, 2019) [1]. Because of their ability to modify pest behavior semiochemicals have

become important tools in environmentally sustainable pest management programs (Howse *et al.*, 1998) ^[45]. Semiochemicals are used by insects to mediate crucial behaviours like mating, oviposition and resource-seeking (Evenden and Silk, 2016) ^[37].

A) Pheromone

Pheromones are chemical substances secreted by an organism that evoke a specific behavioural or physiological response in another individual of the same species (Karlson and Luscher (1959) ^[51]. They represent one of the most extensively studied classes of semiochemicals involved in intraspecific communication. The concept of chemical communication within the same species was initially described by Bethe (1932) ^[17], who introduced the term “ectohormone”. Later, Karlson and Butenandt (1959) ^[50] coined the term pheromone from the Greek “pherein” meaning “to transfer” and “hormon” meaning “to excite”) to describe chemicals released by one individual and received by another individual of the same species producing a specific adaptive response. Pheromones play a vital role in regulating reproductive behaviour, aggregation, trail following, alarm signalling, territorial marking, caste differentiation and social organization in insects (Nordlund *et al.*, 1981; Wyatt, 2014) ^[74, 116]. In insects, pheromones are detected by specialized olfactory sensilla located mainly on the antennae and the resulting signals influence behaviours essential for survival and reproduction. A well-known example is the Queen Mandibular Pheromone (QMP) of the honey bee (*Apis mellifera* L.) whose major component is 9-oxo-2-decenoic acid (9-ODA) suppresses ovarian development in worker bees, maintains colony organization and simultaneously functions as a sex attractant during the nuptial flights of virgin queens (Regnier, 1968; Winston, 1987) ^[87, 111]. Similarly, sex pheromones released by female moths attract conspecific males over long distances, facilitating successful mating and species-specific communication (Carde and Baker, 1984; Wyatt, 2014) ^[116].

Classes of Pheromones

Based on the responses elicited pheromones can be classified into 2 groups-

Releaser Pheromones: Rapid Behavioral Responses

Releaser pheromones are the most widely recognized class of pheromones because they trigger immediate and specific behavioral reactions in members of the same species (Karlson and Luscher, 1959) ^[51]. These responses are typically instinctive, stereotyped and mediated directly through the central nervous system allowing the chemical signal to rapidly initiate a particular behavior (Wyatt, 2003) ^[115].

Primer Pheromones: Long-Term Physiological Effects

Unlike releaser pheromones, primer pheromones produce gradual changes in the recipient's physiological or endocrine system, resulting in delayed but sustained behavioral effects (Karlson and Luscher, 1959) ^[51]. Rather than provoking an immediate response, they regulate developmental and reproductive processes and play a vital role in maintaining social organization and coordinating the activities of members within a social group.

Pheromone reception: Insects are exceptionally skilled at chemical analysis, detecting and interpreting their

surroundings through semiochemicals with remarkable sensitivity. For instance, a male moth can sense the sex pheromones released by a female even when they are present in extremely low concentrations. The antennae function as biological signal converters, transforming chemical cues into electrical nerve impulses that the brain can understand. These signals are detected by specialized sensory structures called sensilla, which are primarily located on the antennae and are then transmitted to the brain for further interpretation. Chemical ecologists take advantage of this highly sensitive olfactory system by using insect antennae as biological sensors to identify pheromones and other semiochemicals. Moreover, the insect olfactory system is highly selective, capable of distinguishing natural pheromones from compounds that differ only slightly in their chemical structure (Leal, 2005) ^[59]. Pheromones may be released by certain insects directly from their glands, while others do so use specialized structures like pheromone brushes or pouches (Mori, 1981) ^[69].

Types of Pheromones

1) Sex pheromone

A sex pheromone is a semiochemical released by an organism (usually female) to attract an individual of the opposite sex (male) of the same species for mating or other activity related to reproduction (Landolt, 1997) ^[57]. Over 150 species of insects are known in which the females produce sex pheromones and about 50 species in which the males do so. It is useful in IPM for monitoring, mass trapping and mating disruption (Bakthavatsalam, 2016) ^[10]. Studies of several Hemiptera (true bugs) have mostly identified male-specific sex pheromones, which may represent historical pre judice rather than taxonomic class bias (Gomez-Diaz, 2013) ^[42]. Sex pheromones have been identified in more than 1600 insect species and are among the most widely studied semiochemicals because of their high species specificity and practical applications in integrated pest management (IPM). The use of synthetic sex pheromones provides an environmentally safe and species-specific alternative to conventional insecticides, thereby reducing pesticide use and preserving natural enemies (Witzgall *et al.*, 2010; Baker, 2016; El-Sayed, 2022) ^[9, 36, 112]. A successful application of sex pheromones is the management of codling moth, *Cydia pomonella* Linn. in apple and pear orchards. Synthetic codlemone is released through pheromone dispensers to disrupt male orientation towards females, thereby reducing mating, oviposition and larval infestation. This mating-disruption technique has been successfully adopted as an important component of IPM and reduces dependence on conventional insecticides (Witzgall *et al.*, 2008) ^[113].

2) Aggregation pheromones

Aggregation pheromones attract individuals of both sexes to food sources, reproductive habitats, or shelter sites. Xiu *et al.* (2024) ^[117] reported that the aggregation pheromone of the stick tea thrips, *Dendrothrips minowai* Priesner (Thysanoptera: Thripidae), increased the capture of adults by 1.2-3.0 times on sticky traps compared with unbaited traps. Furthermore, sticky traps supplemented with the aggregation pheromone of *D. minowai* attracted significantly more adults, capturing 1.2-3.0 times as many individuals as control traps. In the Colorado potato beetle, the male-produced aggregation pheromone ‘Decemdiol’, is

highly attractive to both sexes. In beetles, aggregation pheromones have also been identified whereas, in the predatory stink bug (*Podisus* spp.) they have not yet been identified, suggesting opportunities for developing push-pull systems for behavioural control (Jermy and Butt, 1991)^[47]. Over recent decades, the importance of applying aggregation pheromones in the management of the boll weevil (*Anthonomus grandis* B.), stored product weevils (*Sitophilus zeamais* M., *Sitophilus granaries* L., *Sitophilus oryzae* L.) and pea and bean weevil (*Sitona lineatus* L.) has been demonstrated (Landolt, 1997)^[57]. Ferrugineol-based aggregation pheromone traps used against red palm weevil attract both sexes and are used for mass trapping. Field demonstrations in Goa resulted in about 64 percent reduction in pest damage, demonstrating successful application of aggregation pheromones in IPM (Maruthadurai and Ramesh, 2020)^[62].

3) Alarm pheromones

Alarm pheromones exhibit considerable diversity among insects and function to warn conspecific individuals of potential danger or predator attack (Wyatt, 2003; Verheggen *et al.*, 2010)^[108, 115]. In honey bees, alarm pheromones are produced by the sting apparatus and released during stinging thereby, alerting nearby colony members and triggering defensive behaviour. Similarly, ants utilize trail pheromones secreted from the Dufour's gland to mark pathways that guide nestmates to food sources and back to the nest, ensuring efficient communication and coordinated foraging within the colony (Bruce, T. J. A., 2015)^[121]. Alarm pheromones may also function as kairomones by providing chemical cues that attract predators or parasitoids, thereby benefiting the receiver while adversely affecting the emitting organism (Nordlund and Lewis, 1976)^[73]. Aphid alarm pheromones are among the most extensively studied examples. The alarm pheromone (E)- β -farnesene has been identified in several aphid species including *Acyrtosiphon pisum* H. (pea aphid), *Aphis gossypii* G. (cotton aphid), and *Rhopalosiphum padi* L. (bird cherry-oat aphid) (Bowers *et al.*, 1972)^[19]. Honey bees also release alarm pheromones from their stingers when defending the colony against organisms that threaten the hive (Boch *et al.*, 1962; Shearer and Boch, 1965)^[18, 96]. *Apthana* (Anonymous, 2026)^[7] is an innovative semiochemical-based product containing (E)- β -farnesene (EBF), an aphid alarm pheromone.

It attracts beneficial predators and parasitoids, thereby enhancing natural biological control of aphids and supporting integrated pest management (IPM) while reducing dependence on synthetic insecticides.

4) Trail pheromone

Trail pheromones play a crucial role in the foraging behaviour of social insects, particularly ants (Morgan, 2009)^[68]. By depositing trail pheromones, ants establish chemical pathways that guide other colony members to food sources and back to the nest. The characteristics of trail pheromones vary among species and are influenced by their specific habitats and ecological requirements (Attygalle and Morgan, 1985)^[8, 68]. Synthetic trail pheromones have been incorporated into baits and traps to selectively target pest ant species, demonstrating the strong and consistent influence of these chemical signals on ant behaviour in practical, large-scale pest management applications (Vander Meer, 1996; Rust *et al.*, 2004)^[89, 106]. Trail pheromones have been

investigated for manipulating the foraging behaviour of termites. In *Macrotermes annandalei* S., the compound (Z)-dodec-3-en-1-ol functions as a trail-following pheromone and induces orientation and recruitment behaviour. Synthetic pheromone trails were able to compete with natural trails under field conditions, demonstrating their potential for developing pheromone-based termite management strategies (Sillam-Dusses *et al.*, 2001)^[97]

5) Host marking pheromone

In several phytophagous insect species, females exhibit oviposition behavior by avoiding hosts that have already been marked with host-marking pheromones (HMPs). These pheromones function as chemical stimuli detected through chemoreception, enabling females to differentiate between previously marked and unmarked hosts. Such stimuli are classified as either signals or cues (Seeley, 1989)^[92]. Chemical cues, for example, can indicate the presence of eggs or larvae already occupying a host (Butkewich *et al.*, 1987)^[3]. Field application of glutathione and glutamic acid, identified as HMPs of *Ceratitis cosyra* and *C. rosa*, respectively, reduced fruit-fly infestation in mango by approximately 70-75 percent compared with untreated controls. This demonstrates the potential of HMPs as a non-toxic, behaviour-based component of IPM (Cheseto *et al.*, 2023)^[25].

B) Allelochemicals

Allelochemicals such as protease inhibitors, α -amylase inhibitors, lectins, tannins, phenolic compounds and flavonoids disrupt the digestive physiology of insects by affecting key gut enzymes. Protease inhibitors reduce protein digestion by inhibiting proteolytic enzymes whereas, α -amylase inhibitors prevent efficient starch digestion, resulting in nutrient deficiency and physiological stress in insects (Franco *et al.*, 2002; Zavala *et al.*, 2004)^[40, 121]. According to Nordlund *et al.* (1981) allelochemicals can be separated into signals that are beneficial to the receiver (kairomones), the emitter (allomones) or both (synomones).

1) Allomone

Allomone was proposed by Brown and Eisner (1970)^[20] to denote those substances which convey an advantage upon the emitter. Allomone is a chemical substance produced and released by one organism that affects the behavior or physiology of an individual of another species in a way that benefits the emitter, while the receiving organism gains no benefit and may even be harmed (Eisner and Meinwald, 1995)^[35]. Different types of behaviours are mediated by allomones. Key among these are their roles as defensive secretions against predators or other natural enemies, such as the formic acid sprayed by formicine ants and the venom from many social wasps, social bees, and ants (Yusuf, 2021)^[119]. For example, Defensive chemicals released by stink bugs or bombardier beetles that repel predators. Bark beetles communicate via pheromones to announce a new food resource (i.e. dead trees, roots, living trees, etc.) ultimately resulting in the accumulation of a large concentration of bark beetles. Select species of bark beetles have the capability to emit pheromones that can negatively affect the behavioral response of another competing species of bark beetles when both species are attempting to inhabit the loblolly pine tree (Wood, 1982)^[114].

2) Kairomone

Kairomones are interspecific semiochemicals or mixtures of semiochemicals produced by one species that trigger responses beneficial to an individual of another species receiving the signal. They are important in biological control programs because of the significant role of semiochemicals in host-plant selection by phytophagous insects (Bernays, 1994) [15]. Kairomone based lures are applied in crop systems, where the surrounding plant odours influence the ability of natural enemies to locate herbivorous insects (Schroder and Hilker, 2008; Randlkofer *et al.*, 2010) [44, 84, 91].

3) Apneumones

Chemical compounds released by non-living materials that trigger beneficial behavioural or physiological responses in one organism while potentially causing harmful effects to other species interacting with the same material. A rare example is the release of hexanal and 2-methyl-2-butanol from rabbit feces, which attracts female sandflies seeking suitable sites for egg-laying. These types of allelochemicals demonstrate the complexity of chemical communication among species, producing interactions that can range from mutually beneficial to detrimental depending on the organisms involved (Abd El-Ghany, 2020) [2]. Rare instances of these allelochemicals have been documented in the literature, such as the attraction of sandfly females for oviposition by hexanal and 2-methyl-2-butanol emitted by rabbit faeces (Dougherty *et al.*, 1995) [32].

1) Synomones

A synomone is an interspecific chemical signal that is beneficial to both interacting organisms, namely the emitter and the receiver. For example, the floral synomone of certain *Bulbophyllum* species (Orchidaceae) attracts male fruit flies (Tephritidae: Diptera), which act as pollinators. The orchid flowers are successfully pollinated, while the male Dacini fruit flies obtain a sex pheromone precursor or enhancer. The floral synomone also serves as a reward to pollinators and occurs in the form of phenylpropanoids, such as methyl eugenol (Tan *et al.*, 2002; Nishida *et al.*, 2004; Tan *et al.*, 2006) [72] or phenyl butanoids, such as raspberry ketone (Tan and Nishida, 2000) and zingerone (Tan and Nishida, 2005). They are often released in response to herbivore attack, attracting natural enemies of herbivores and thereby reducing plant damage (Karban and Baldwin, 1997; Dicke and Hilker, 2003) [30, 44, 49]. These cues are utilized by parasitoids belonging to the families Eulophidae, Scelionidae, and Mymaridae in various ecosystems involving both arboreal perennial plants and herbaceous annual plants (Hilker and Meiners, 2002; Colazza *et al.*, 2004) [26, 44]. Plant-derived synomones released by maize following *Chilo partellus* S. damage, particularly (E)- β -farnesene and (Z)-3-hexenyl acetate, attract the parasitoid *Cotesia flavipes* C., thereby enhancing indirect plant defence and offering potential for parasitoid-based pest management (Ngumbi *et al.*, 2005) [71].

Use of Semiochemicals In Integrated Pest Management

1) Mass trapping

Mass trapping is an important component of integrated pest management (IPM) for managing soil-dwelling scarab beetles by suppressing adult populations and consequently reducing larval infestations. After successful preliminary

experiments, large-scale mass trapping of the American palm weevil was initiated in 1991 on two major oil palm plantations in Costa Rica, encompassing areas of 6514 ha and 8719 ha, respectively (Oehlschlager *et al.*, 2002) [75]. Galko *et al.*, (2016) [41] evaluated the effectiveness of six pheromone-based traps for managing the European spruce bark beetle. The study compared four commercially available traps with two newly developed designs: BEKA (B), Ecotrap (E), Cross trap (K), Lindgren funnel trap (L), Funnel trap (P), and Theysohn (T). Differences in trapping performance were primarily attributed to variations in trap design. Field evaluations were carried out across ten locations over three consecutive growing seasons. The strengths and limitations of each trap type, identifying operating lifespan and storage durability as the major drawbacks affecting their practical use. Methyl eugenol-baited PAU fruit-fly traps used for managing *Bactrocera* spp. in guava during 2017 and 2018 in Punjab. The traps recorded peak catches of 801.5 and

720.4 flies per trap per week, respectively. Fruit infestation was reduced from 67-81 percent in untreated plots to 45-48 percent in trapped plots, while fruit yield increased from 8.1-8.8 to 12.6-15.4 kg per tree (Sharma *et al.*, 2022) [95]. The Japanese beetle, *Popillia japonica* N. (Coleoptera: Scarabaeidae), has recently been effectively controlled using this approach (Pinero and Dudenhoefter, 2018). Mass trap synthetic blend of 3Z-hexen-1-ol, α -pinene, hexyl acetate, benzyl alcohol, and 6Z nonenal in funnel traps yielded the highest capture of adult Mass trap synthetic blend of 3Z-hexen-1-ol, α -pinene, hexyl acetate, benzyl alcohol, and 6Z nonenal in funnel traps yielded the highest capture of adult *Diaphania indica* Saunders (Lepidoptera: Crambidae) in snakegourds (Debnath *et al.*, 2023) [28]. Pawar *et al.*, (2009) [77] evaluated a sex pheromone-based IPM strategy against *Leucinodes orbonalis* in brinjal at MPKV, Rahuri. Mass trapping using Leucinlure-baited funnel traps at 1 trap per 100 square meter, integrated with cultural and botanical practices, reduced shoot infestation by 80.44 percent compared with the untreated control and 61.64 percent compared with IPM without mass trapping. The treatment also increased yield by 44.75 percent over the untreated control, demonstrating the effectiveness of pheromone-based mass trapping

Table 1: Effectiveness of pheromone-based mass trapping against brinjal shoot and fruit borer

Treatment/Parameter	Observation/Result
Pest	<i>Leucinodes orbonalis</i> Guenée
Crop	Brinjal (<i>Solanum melongena</i> L.)
Pheromone lure	Leucilure (sex pheromone)
Trap type	Plastic funnel trap
Trap density	1 trap per 100 square meter
Reduction in shoot infestation over untreated control	80.44 percent
Reduction in shoot infestation due to mass trapping	61.64 percent
Increase in yield over untreated control	44.75 percent
Increase in yield due to mass trapping	11.76 percent
Study period	2006-2008
Study location	MPKV, Rahuri, Maharashtra, India

Types of Pheromone Traps

Delta Traps: Triangular sticky traps mainly used to monitor moth populations in crop fields. (Raj, 2025) ^[82]

Funnel Traps: These traps contain a pheromone lure and a funnel-shaped entrance that guides insects into a collection chamber, preventing their escape. They are suitable for capturing large numbers of insects (Raj, 2025) ^[82].

Water Traps: Insects are attracted by the pheromone lure and fall into a container filled with water, where they drown (Raj, 2025) ^[82].

Sticky Traps: These traps have an adhesive-coated surface that captures insects when they land on or come into contact with it. They are commonly used for pest monitoring (Raj, 2025) ^[82].

Mass Trapping Devices: These are larger traps designed to capture a high number of insects, helping to reduce pest populations rather than only monitoring their presence (Raj, 2025) ^[82].

1) Mating disruption

Mating disruption is a semiochemical-based pest management strategy that interferes with the pheromone communication system of insects, preventing successful mate location and copulation (Shani, 2001) ^[93]. Mating disruption was first discussed by the scientists of an institute in Bordeaux, France in 1974. These pheromones confuse individuals, hinder their ability to locate mates, and reduce successful mating, ultimately lowering reproductive potential (Carde and Minks, 1995). This technique relies on artificially synthesized pheromones, usually consisting of blends of major and minor chemical components, designed to imitate the activity of naturally produced pheromones (Bakthavatsalam, 2016) ^[10]. Various mating disruption mechanisms have been postulated (Bartell 1982; Carde and Minks 1995; Miller *et al.* 2006) ^[13, 67], which can be divided into two main categories: competitive and non-competitive (Miller *et al.*, 2006) ^[67]. Competitive disruption includes competitive attraction (false-trail-following, confusion), induced allopatriy, and induced arrestment, whereas noncompetitive disruption involves other mechanisms, such as suppressed calling/mating, camouflage, sensory imbalance, induced allochroony, and desensitisation (habituation) (Miller and Gut 2015) ^[66]. Mating disruption devices, several microencapsulated dispensers, manually applied dispensers (pheromone traps, PB rope, SPLAT), and high-emission dispensers are now available in the market. Consequently, this innovative technology may assist in addressing the gaps in current IPM programmes for sustainable pest management (Mevada *et al.*, 2023) ^[63]. In overall, MD represents a key behavioral component in reducing pesticide reliance and promoting sustainable management of stored-product pests. (Adamic Zamljen, 2026) ^[5, 120]. Mating disruption technology has been commercially adopted and is being increasingly utilized for the management of the vine mealybug, *Planococcus ficus* S., while its application against the California red scale, *Aonidiella aurantii* M., remains comparatively limited (Franco, 2022) ^[39]. The strategy is based on the use of electrostatically charged powders, able to adhere to insect cuticles, as carriers for active ingredients such as

pheromones, entomopathogens, and insecticides (Trematerra, 2012) ^[105]. Paddy yellow stem borer *Scirpophaga incertulas* Walke (Lepidoptera: Crambidae) are effectively managed by the Pheron RSB mating disruption dispenser (Iqbal *et al.*, 2023) ^[46]. The mating disruption technique was used in pea fields, for five years period to control pea moth, *Cydia nigricana* F. by assessing male attraction to monitor traps, pod infestation, and larval age structure in pheromone-treated and untreated grain. Cellulose pheromone dispensers were manually attached to the top shoots of pea plants and released 540 mg per hectare per day synthetic pheromone (E8, E10-dodecadien-1-yl acetate). The dispensers had a half-life of about 30 days. Although male attraction to pheromone monitoring traps was largely suppressed at the edges and within MD fields (Saucke *et al.*, 2014) ^[90]. PB-Rope L sex pheromone dispensers were used for mating disruption of pink bollworm in cotton. The treatment reduced male moth catches by 79.4 and 93.8 percent during two successive seasons and reduced boll damage and larval populations, while increasing seed-cotton yield by 32.1 and 40.9 percent, respectively (Patil *et al.* (2007) ^[76]. Yeast-derived sex pheromones used for mating disruption of *Helicoverpa armigera* in cotton. Three years of field trials in Greece showed that yeast-produced pheromones were as effective as synthetic pheromones in disrupting male orientation (Raptopoulos *et al.*, 2025) ^[85]. Ricciardi *et al.* (2024) ^[4] evaluated a biodegradable double-tube sex pheromone dispenser (Isonet® L CG-BIOX235) for simultaneous mating disruption of *Lobesia botrana* and *Cryptoblabes gnidiella* in Italian vineyards. Field trials conducted in Tuscany and Apulia during 2022-2023 showed that the dispenser significantly reduced infestation of both pests compared with untreated vineyards.

2) Monitoring

One of the most common and successful practical applications of semiochemicals is in pest detection and monitoring (Witzgall *et al.*, 2010) ^[112]. Pheromone traps can detect insect pests and are also valuable for estimating population density and seasonal fluctuations to identify the initial peak of flight activity (Weinzierl *et al.* 2005) ^[110]. Rhainds *et al.* (2016) ^[88] evaluated the abundance of male *Choristoneura fumiferana* C. (Lepidoptera: Tortricidae) in Canada using a surveillance method based on pheromone-baited traps. Variability in trap catches and its association with later infestations was utilized to develop a decision-support model (Bruce and Smart, 2009) ^[122]. New technologies have developed in the recent years for pest detection and surveillance systems, based on acoustic transducers that are capable to detect the sounds of the insects and then send electronic signals to a central station where the trap locations are identified (Beroza, 2002) ^[16]. Other systems based on an automatic counting of the captured insects fitted with crossing transducers integrated with data transmission systems have been created (Tabuchi *et al.*, 2006) ^[98]. In an interesting different method, Guarnieri *et al.*, (2011) ^[43] developed an automated electronic trap for monitoring the codling moth by altering a commercial trap-specific for the insect with the application of a mobile phone camera and transmit the data to a distant server. This type of technology is likely to be most financially feasible for detection of important exotic pests where the initial incursion of a new moth is the most

valuable task. IoT-based traps with accurate visual and olfactory cues have been effectively used to monitor oriental fruit flies infestation (Jiang *et al.*, 2024)^[48]. Rajashekhar *et al.*, 2024^[83] demonstrated that pheromone-based monitoring integrated with biological, botanical and need-based insecticide applications effectively managed *Spodoptera frugiperda* S. in maize. The IPM strategy increased yield by 17.49-24.87 percent over farmers' practices.

Recent strategies in Semiochemicals Application in Integrated Pest Management

1) Push and pull strategy The term push-pull was first conceived by Pyke *et al.*, (1987)^[81] as a strategy for insect pest management. Push-pull experiments using a combination of repellents and attractants could be considered a sustainable alternative to conventional insecticides. Repellents could 'push' away insects from vulnerable crops whereas at the same time attractants could 'pull' them into annihilating traps (Cook *et al.*, 2007; Khan *et al.*, 2010; Reddy and Guerrero, 2010; Sharma *et al.*, 2019)^[27, 54, 86, 94]. Push-pull and habitat

management are core components of Integrated Pest Management (IPM) programs that aim to synergize multiple compatible tactics for long-term pest control (Barzman *et al.*, 2015)^[14]. Pull plants attract insect pests using volatile compounds, visual signals, and arrestant cues. They may also release oviposition stimulants and offer better nutrition to maintain the pests (Eigenbrode *et al.*, 2016)^[34]. In the maize-growing farming systems of East Africa, combining push-pull with peripheral vegetation like hedgerows and woodlots has enhanced the benefits of pest and weed control, while offering additional ecosystem services such as soil and water conservation, fodder production, and carbon sequestration (Khan *et al.*, 2016)^[55]. Use of the push-pull semiochemical technique is effective in reducing *Ips* (-66 percent) and *Dendroctonus* (-54 percent) compared to control;

(2) Among push-pull treatment sources, conspecific semiochemicals combined with heterospecific and NHVs provide the maximum reduction for *Dendroctonus* (Afzal *et al.*, 2023)^[6].

Table 2: Models of "push-pull" habitat management strategy for control of insect pests

Crop	Target pest	Push component	Pull component	Mechanism / outcome	Reference
Maize	<i>Chilo partellus</i>	<i>Desmodium</i> spp.	Napier grass (<i>Cenchrus purpureus</i>)	<i>Desmodium</i> repels stemborer moths and suppresses <i>Striga</i> , while Napier grass attracts and traps moths	Khan <i>et al.</i> (2000) ^[53]
Maize	<i>Spodoptera frugiperda</i>	<i>Desmodium</i> spp.	Napier grass / <i>Brachiaria</i> spp.	Reduced fall armyworm infestation and plant damage; increased maize yield	Midega <i>et al.</i> (2018) ^[65]
Maize	Stemborers	<i>Desmodium</i> spp.	Napier grass	Repulsion of adult moths from maize and increased mortality of larvae on trap plants	Khan <i>et al.</i> (2008) ^[52]
Cotton	<i>Helicoverpa armigera</i>	Neem-based repellent	Pigeon pea / okra	Repels oviposition from cotton and concentrates pest activity on trap crops	Duraimurugan and Regupathy (2005) ^[33]

Likewise, combining push-pull with flower strips and beetle banks has increased the abundance and diversity of natural enemies in brassica crops in New Zealand, resulting in improved biological control of aphids and moths (Tompkins, 2010)^[104].

2) Lure and infect

In recent years, the use of semiochemicals combined with entomopathogenic fungi has emerged as a promising strategy for pest management in agriculture. This method is often referred to as "lure and infect" and it utilizes natural dispersal mechanisms of pathogens while increasing their effectiveness through targeted application (Vega *et al.*, 2009)^[107]. The lure-and-infect (also known as attract-and-infect) strategy has demonstrated promising capacity for controlling several dipteran pests, including tsetse flies and Mediterranean fruit flies (Maniania, 2002; Navarro-Llopis *et al.*, 2013; Dimbi *et al.*, 2013)^[31, 61, 70]. Applying this strategy to *Beauveria bassiana* B. presents a major technical challenge: many highly potent attractant components or their associated chemical environments can suppress conidial germination and mycelial growth of *B. bassiana* (Toledo *et al.*, 2007; Khun *et al.*, 2021)^[56, 103]. A study by Mfuti *et al.*, (2017)^[64] investigated the combined use of *Metarhizium anisopliae* M. and the thrips attractant Lurem-TR for managing bean flower thrips on cowpeas. Their field experiments compared spot and cover spray applications, where the spot application ("lure-and-infect") was the most effective. Thrips density was reduced from 67.4 ± 10.30 thrips per plant in the control to 30.5 ± 6.0 thrips per plant. Importantly, this method required 81.2 per cent less

inoculum than cover sprays, making it a cost-effective approach for small-scale farmers. Dembilio *et al.*, (2018)^[29] developed a lure and-infect device using the red palm weevil aggregation pheromone to attract adults and *Beauveria bassiana* to infect them. Laboratory, semi-field and field studies demonstrated the potential of the device for controlling the red palm weevil. *Metarhizium brunneum*-based lure-and-infect device effectively suppressed *Drosophila suzukii* M. The treatment caused 48percent mortality in untreated males and reduced female fecundity by 84.7 percent, indicating its potential as an eco-friendly IPM strategy (Yousef *et al.*, 2018)^[118].

3) Integration of semiochemicals and remote sensing technologies

Researchers have employed drones equipped with sensors to detect volatile organic compounds (VOCs) emitted by plants under stress. These VOCs serve as semiochemicals that can indicate factors such as drought, nutrient deficiencies, or pest damage. By combining this technology with remote sensing data on vegetation health, researchers can assess the physiological condition of crops or natural vegetation with high spatial resolution (Lasa *et al.*, 2024)^[58]. Bapatla *et al.*, (2026)^[12] integrated pheromone-trap monitoring with Landsat-8 remote sensing to monitor the yellow stem borer, *Scirpophaga incertulas*, in rice fields of Srikakulam, Andhra Pradesh. The study used pheromone traps along with NDVI and land surface temperature (LST) to identify pest hotspots. Smart trap containing a pheromone-kairomone lure and automatic imaging for remote monitoring of codling moth in apple and pear orchards. The system

allowed trap catches to be monitored remotely, reducing the need for frequent manual inspection (Preti *et al.*, 2021)^[79].

Conclusion

Semiochemicals are important behaviour-based tools in IPM that manipulate insect behaviour for detection, monitoring and pest suppression. Pheromones and allelochemicals are used in mass trapping, mating disruption, push-pull strategies, host-marking manipulation and lure-and-infect systems. Successful examples in brinjal, cereals and lepidopteran pests show that they can effectively reduce pest populations when combined with other IPM methods. Recent advances such as controlled-release formulations, automated traps, IoT monitoring and remote sensing are making semiochemical-based management more precise, scalable and timely. However, challenges remain regarding formulation stability, release rate, trap design, environmental variation, cost and compatibility with biological control agents. Overall, the future of semiochemical-based IPM depends on integrating chemical ecology, biological control, digital technologies, remote sensing and precision agriculture. This integration can provide targeted, economical, environmentally safe and climate-resilient pest management, provided that technologies are further validated under field conditions and made accessible to farmers

References

1. Abd El-Ghany NM. Semiochemicals for controlling insect pests. *J Plant Prot Res.* 2019;59:1-11. doi:10.24425/jppr.2019.126036.
2. Abd El-Ghany NM. Pheromones and chemical communication in insects. In: Kontogiannatos K, Kourti A, Mendes D, editors. *Pests, weeds and diseases in agricultural crop and animal husbandry production.* 2020. p.1-13.
3. Butkewich SL, Prokopy RJ, Green TA. Discrimination of occupied host fruit by plum curculio females (Coleoptera: Curculionidae). *J Chem Ecol.* 1987;13:1833-1841. doi:10.1007/BF01013232.
4. Ricciardi R, De Fazi L, Danna G, Savino F, Ladurner E, Iodice A, *et al.* Simultaneous mating disruption of two moth pests of the vineyard (*Lobesia botrana* and *Cryptoblabes gnidiella*) through a biodegradable sex pheromone dispenser. *Environ Sci Pollut Res.* 2024;31:43865-43873. doi:10.1007/s11356-024-33980-w.
5. Zamljen SA, Bohinc T, Trdan S. Mating disruption as a pest management strategy: expanding applications in stored product protection. *Agronomy.* 2026;16(1):39. doi:10.3390/agronomy16010039.
6. Afzal S, Nahrung HF, Lawson SA, Hayes RA. How effective are push-pull semiochemicals as deterrents for bark beetles? A global meta-analysis of thirty years of research. *Insects.* 2023;14(10):812. doi:10.3390/insects14100812.
7. Anonymous. BASF launches new beneficial insect attractant, Aphena®. BASF Agricultural Solutions UK. 2026. Available from: <https://www.agricentre.basf.co.uk/en/News-Events/BASF-Ag-Solutions-News/BASF-launches-new-beneficial-insect-attractant-Aphena-108672.html>
8. Attygalle AB, Morgan ED. Ant trail pheromones. In: Berridge MJ, Treherne JE, Wigglesworth VB, editors. *Advances in insect physiology.* Vol. 18. Academic Press; 1985. p.1-30. doi:10.1016/S0065-2806(08)60038-7.
9. Baker TC, Zhu JJ, Millar JG. Delivering on the promise of pheromones. *J Chem Ecol.* 2016;42(7):553-556. doi:10.1007/s10886-016-0744-5.
10. Bakthavatsalam N. Semiochemicals. In: Omkar, editor. *Eco-friendly pest management for food security.* Academic Press; 2016. p.563-611.
11. Bakthavatsalam N, Subaharan K. Innovations in insect pest management: interventions using insect-derived volatiles. *Indian J Plant Genet Resour.* 2016;29:399-401.
12. Bapatla KG, Bandaru G, Shyam CS, Panda BB. Integrating pheromone trap monitoring with remote sensing indices for enhanced surveillance of yellow stem borer in rice. *Ann Appl Biol.* 2026;188(2):495-502. doi:10.1111/aab.70069.
13. Bartell RJ. Mechanisms of communication disruption by pheromone in the control of Lepidoptera: a review. *Physiol Entomol.* 1982;7(4):353-364. doi:10.1111/j.1365-3032.1982.tb00310.x.
14. Barzman M, Barberi P, Birch ANE, Boonekamp P, Dachbrodt-Saaydeh S, Graf B, *et al.* Eight principles of integrated pest management. *Agron Sustain Dev.* 2015;35(4):1199-1215.
15. Bernays EA, Chapman RF. Host-plant selection by phytophagous insects. Chapman and Hall; 1994.
16. Beroza M. More efficient and environmentally desirable means of detecting insects entering lure-baited traps or attractive areas. US Patent No. 0144452. U.S. Patent and Trademark Office; 2002.
17. Bethe A. Vernachlässigte Hormone. *Naturwissenschaften.* 1932;20(11):177-181. doi:10.1007/BF01504737.
18. Boch R, Shearer DA, Stone BC. Identification of isoamyl acetate as an active component in the sting pheromone of the honey bee. *Nature.* 1962;195:1018-1020.
19. Bowers WS, Nault LR, Webb RE, Dutky SR. Aphid alarm pheromone: isolation, identification, synthesis. *Science.* 1972;177(4054):1121-1122.
20. Brown WL, Eisner T, Whittaker RH. Allomones and kairomones: transspecific chemical messengers. *BioScience.* 1970;20(1):21-22.
21. Bruce TJA, Aradottir GI, Smart LE, Martin JL, Caulfield JC, Doherty A, *et al.* The first crop plant was genetically engineered to release an insect pheromone for defense. *Sci Rep.* 2015;5:11183. doi:10.1038/srep11183.
22. Bruce TJ, Smart LE. Orange wheat blossom midge, *Sitodiplosis mosellana*, management. *Outlooks Pest Manag.* 2009;20(2):89-94.
23. Cardé RT, Baker TC. Sexual communication with pheromones. In: Bell WJ, Cardé RT, editors. *Chemical ecology of insects.* Chapman and Hall; 1984. p.355-383.
24. Cardé RT, Minks AK. Control of moth pests by mating disruption: successes and constraints. *Annu Rev Entomol.* 1995;40:559-585. doi:10.1146/annurev.en.40.010195.003015.
25. Cheseto X, Kirwa H, Mohamed SA, Ekesi S, Beck JJ, Torto B. Field evaluation of glutathione and glutamic acid as host marking pheromones for control of

- tephritid fruit flies in a mango orchard in Kenya. *Pest Manag Sci.* 2023;79(4):1585-1592. doi:10.1002/ps.7331.
26. Colazza S, Fucarino A, Peri E, Salerno G, Conti E, Bin F. Insect oviposition induces volatile emission in herbaceous plants that attracts egg parasitoids. *J Exp Biol.* 2004;207:47-53.
 27. Cook SM, Khan ZR, Pickett JA. The use of push-pull strategies in integrated pest management. *Annu Rev Entomol.* 2007;52:375-400. doi:10.1146/annurev.ento.52.110105.091407.
 28. Debnath R, Bhattacharyya B, Koner A, Barik A. Semiochemicals from *Trichosanthes anguina* (Cucurbitaceae) plants influence behavior in *Diaphania indica*. *Pest Manag Sci.* 2023;79:4295-4308.
 29. Dembilio O, Moya P, Vacas S, Ortega-García L, Quesada-Moraga E, Jaques JA, *et al.* Development of an attract-and-infect system to control *Rhynchophorus ferrugineus* with the entomopathogenic fungus *Beauveria bassiana*. *Pest Manag Sci.* 2018;74(8):1861-1869. doi:10.1002/ps.4888.
 30. Dicke M, Hilker M. Induced plant defences: from molecular biology to evolutionary ecology. *Basic Appl Ecol.* 2003;4(1):3-14.
 31. Dimbi S, Maniania NK, Ekesi S. Horizontal transmission of *Metarhizium anisopliae* in fruit flies and effect of fungal infection on egg laying and fertility. *Insects.* 2013;4(2):206-216. doi:10.3390/insects4020206.
 32. Dougherty MJ, Guerin P, Ward RD. Identification of oviposition attractants for the sandfly *Lutzomyia longipalpis* (Diptera: Psychodidae) present in volatiles of faeces from vertebrates. *Physiol Entomol.* 1995;20(1):23-32. doi:10.1111/j.1365-3032.1995.tb00797.x.
 33. Duraimurugan P, Regupathy A. Push-pull strategy with trap crops, neem and nuclear polyhedrosis virus for insecticide resistance management in *Helicoverpa armigera* (Hübner) in cotton. *Am J Appl Sci.* 2005;2(6):1042-1048. doi:10.3844/ajassp.2005.1042.1048.
 34. Eigenbrode SD, Birch ANE, Lindzey S, Meadow R, Snyder WE. A mechanistic framework to improve understanding and applications of push-pull systems in pest management. *J Appl Ecol.* 2016;53(1):202-212.
 35. Eisner T, Meinwald J. Chemical ecology. *Proc Natl Acad Sci U S A.* 1995;92(1):1. doi:10.1073/pnas.92.1.1.
 36. El-Sayed AM, Ganji S, Gross J, Giesen N, Rid M, Lo PL, *et al.* Correction to: Climate change risk to pheromone application in pest management. *Sci Nat.* 2022;109:8. doi:10.1007/s00114-021-01770-w.
 37. Evenden ML, Silk PJ. The influence of Canadian research on semiochemical-based management of forest insect pests in Canada. *Can Entomol.* 2016;148(S1):S170-S209. doi:10.4039/tce.2016.36.
 38. Firn R. *Nature's chemicals: the natural products that shaped our world.* Oxford: Oxford University Press; 2011.
 39. Franco JC, Cocco A, Lucchi A, Mendel Z, Suma P, Vacas S, *et al.* Scientific and technological developments in mating disruption of scale insects. *Entomol Gen.* 2022;42(2):251-273.
 40. Franco OL, Rigden DJ, Melo FR, Grossi-de-Sa MF. Plant α -amylase inhibitors and their interaction with insect α -amylases. *Eur J Biochem.* 2002;269(2):397-412.
 41. Galko J, Nikolov C, Kunca A, Vakula J, Gubka A, Zubrik M. Effectiveness of pheromone traps for the European spruce bark beetle: a comparative study of four commercial products and two new models. *For J.* 2016;62(4):207-215.
 42. Gomez-Diaz C, Benton R. The joy of sex pheromones. *EMBO Rep.* 2013;14(10):874-883. doi:10.1038/embor.2013.140.
 43. Guarnieri A, Maini S, Molari G, Rondelli V. Automatic trap for moth detection in integrated pest management. *Bull Insectol.* 2011;64:247-251.
 44. Hilker M, Rohfritsch O, Meiners T. The plant's response towards insect egg deposition. In: Hilker M, Meiners T, editors. *Chemoecology of insect eggs and egg deposition.* 2002. p.205-233.
 45. Howse PE, Stevens IDR, Jones OT. *Insect pheromones and their use in pest management.* Chapman and Hall; 1998.
 46. Iqbal M, Marman M, Arintya F, Broms K, Clark T, Srigiriraju L. Mating disruption technology: an innovative tool for managing yellow stem borer (*Scirpophaga incertulas* Walker) of rice in Indonesia. *J Entomol Indones.* 2023;20:129-140.
 47. Jermy T, Butt BA. Method for screening sex pheromone extracts of the Colorado potato beetle. *Entomol Exp Appl.* 1991;59(1):75-78.
 48. Jiang JA, Liu YY, Liao MS, Yang EC, Chen MY, Chuang YY, *et al.* Complementary use of visual and olfactory cues to assess capture of *Bactrocera dorsalis* (Hendel): implementation and field verification via an IoT-based automatic monitoring system. *Proc Jpn Acad Ser B Phys Biol Sci.* 2024;100:68-85.
 49. Karban R, Baldwin IT. *Induced responses to herbivory.* Chicago: University of Chicago Press; 1997.
 50. Karlson P, Butenandt A. Pheromones (ectohormones) in insects. *Annu Rev Entomol.* 1959;4:39-58. doi:10.1146/annurev.en.04.010159.000351.
 51. Karlson P, Luscher M. Pheromones: a new term for a class of biologically active substances. *Nature.* 1959;183(4653):55-56. doi:10.1038/183055a0.
 52. Khan ZR, Midega CAO, Amudavi DM, Hassanali A, Pickett JA. On-farm evaluation of the 'push-pull' technology for the control of stemborers and *Striga* weed on maize in western Kenya. *Field Crops Res.* 2008;106(3):224-233. doi:10.1016/j.fcr.2007.12.002.
 53. Khan ZR, Pickett JA, Van den Berg J, Wadhams LJ, Woodcock CM. Exploiting chemical ecology and species diversity: stem borer and *Striga* control for maize and sorghum in Africa. *Pest Manag Sci.* 2000;56(11):957-962. doi:10.1002/1526-4998(200011)56:11.
 54. Khan ZR, Midega CAO, Bruce TJA, Hooper AM, Pickett JA. Exploiting phytochemicals for developing a 'push-pull' crop protection strategy for cereal farmers in Africa. *J Exp Bot.* 2010;61(15):4185-4196. doi:10.1093/jxb/erq229.
 55. Khan ZR, Midega CA, Hooper A, Pickett J. Push-pull: chemical ecology based integrated pest management technology. *J Chem Ecol.* 2016;42(7):689-697.
 56. Khun KK, Ash GJ, Stevens MM, Huwer RK, Wilson BA. Compatibility of *Metarhizium anisopliae* and *Beauveria bassiana* with insecticides and fungicides

- used in macadamia production in Australia. *Pest Manag Sci.* 2021;77(2):709-718. doi:10.1002/ps.6065.
57. Landolt PJ. Sex attractant and aggregation pheromones of male phytophagous insects. *Am Entomol.* 1997;43(1):12-22. doi:10.1093/ae/43.1.12.
 58. Lasa R, Rull J, Suárez L, Mello Garcia FR, Williams T, Díaz-Fleischer F. Monitoring and mass trapping of fruit flies (Diptera: Tephritidae) in the Americas. In: *Management of fruit flies in the Americas.* 2024. p.67-126.
 59. Leal WS. Pheromone reception. In: Schulz S, editor. *The chemistry of pheromones and other semiochemicals II. Topics in Current Chemistry.* Vol. 240. Berlin: Springer; 2005. doi:10.1007/b98314.
 60. Manda RR, Addanki VA, Srivastava S. Microbial biopesticides and botanicals as an alternative to synthetic pesticides in sustainable agricultural production. *Plant Cell Biotechnol Mol Biol.* 2020;21(61-62):31-48.
 61. Maniania NK. A low-cost contamination device for infecting adult tsetse flies, *Glossina* spp., with the entomopathogenic fungus *Metarhizium anisopliae* in the field. *Biocontrol Sci Technol.* 2002;12(1):59-66. doi:10.1080/09583150120110662.
 62. Maruthadurai R, Ramesh R. Mass trapping of red palm weevil and rhinoceros beetle in coconut with aggregation pheromone. *Indian J Entomol.* 2020;82(3):439-441. doi:10.5958/0974-8172.2020.00114.5.
 63. Mevada RR, Sisodiya DB, Parmar RG, Prajapati DR. Mating disruption: an ecological step towards sustainable pest management. *J Eco-Friendly Agric.* 2023;18(1):144-150. doi:10.5958/2582-2683.2023.00025.4.
 64. Mfuti DK, Niassy S, Subramanian S, du Plessis H, Ekesi S, Maniania NK. Lure and infect strategy for application of entomopathogenic fungus for the control of bean flower thrips in cowpea. *Biol Control.* 2017;103:9-16. doi:10.1016/j.biocontrol.2016.08.005.
 65. Midega CAO, Pittchar JO, Pickett JA, Hailu GW, Khan ZR. A climate-adapted push-pull system effectively controls fall armyworm, *Spodoptera frugiperda* (J. E. Smith), in maize in East Africa. *Crop Prot.* 2018;105:10-15. doi:10.1016/j.cropro.2017.11.003.
 66. Miller JR, Gut LJ. Mating disruption for the 21st century: matching technology with mechanism. *Environ Entomol.* 2015;44(3):427-453. doi:10.1093/ee/nvv052.
 67. Miller JR, Gut LJ, de Lame FM, Stelinski LL. Differentiation of competitive vs. non-competitive mechanisms mediating disruption of moth sexual communication by point sources of sex pheromone (Part 1): theory. *J Chem Ecol.* 2006;32(10):2089-2114.
 68. Morgan ED. Trail pheromones of ants. *Physiol Entomol.* 2009;34(1):1-17.
 69. Mori K. The synthesis of insect pheromones. In: *Total synthesis of natural products.* Vol. 4. 1981. p.1-183.
 70. Navarro-Llopis V, Primo J, Vacas S. Efficacy of attract-and-kill devices for the control of *Ceratitis capitata*. *Pest Manag Sci.* 2013;69(10):1114-1120. doi:10.1002/ps.3480.
 71. Ngumbi EN, Ngi-Song AJ, Njagi ENM, Torto R, Wadhams LJ, Birkett MA, et al. Responses of the stem borer larval endoparasitoid *Cotesia flavipes* to plant-derived synomones: laboratory and field cage experiments. *Biocontrol Sci Technol.* 2005;15(3):271-279. doi:10.1080/09583150400016985.
 72. Nishida R, Tan KH, Wee SL, Hee AKW, Toong YC. Phenylpropanoids in the fragrance of the fruit fly orchid, *Bulbophyllum cheiri*, and their relationship to the pollinator, *Bactrocera papayae*. *Biochem Syst Ecol.* 2004;32(3):245-252. doi:10.1016/S0305-1978(03)00179-0.
 73. Nordlund DA, Lewis WJ. Terminology of chemical releasing stimuli in intraspecific and interspecific interactions. *J Chem Ecol.* 1976;2(2):211-220.
 74. Nordlund DA, Jones RL, Lewis WJ. *Semiochemicals and their role in pest control.* New York: John Wiley and Sons; 1981. p.306.
 75. Oehlschlager AC, Chinchilla C, Castillo G, Gonzalez L. Control of red ring disease by mass trapping of *Rhynchophorus palmarum* (Coleoptera: Curculionidae). *Fla Entomol.* 2002;85(3):507-513.
 76. Patil SB, Bambawale OM, Tanwar RK, Udikeri SS, Renuka HB. Management of pink bollworm (*Pectinophora gossypiella* Saunders) in cotton through mating disruption. *Pestic Res J.* 2007;19(2):201-204.
 77. Pawar DB, Bhalekar MN, Chandele AG, Ilhe BM, Shinde HN. Sex pheromone based IPM technology for brinjal shoot and fruit borer *Leucinodes orbonalis* Guenée (Lepidoptera: Pyralidae). *Pest Manag Horticult Ecosyst.* 2009;15(2):114-120.
 78. Piñero JC, Dudenhoefter AP. Mass trapping designs for organic control of the Japanese beetle, *Popillia japonica* (Coleoptera: Scarabaeidae). *Pest Manag Sci.* 2018;74(7):1687-1693. doi:10.1002/ps.4862.
 79. Preti M, Favaro R, Knight AL, Angeli S. Remote monitoring of *Cydia pomonella* adults among an assemblage of nontargets in sex pheromone-kairomone-baited smart traps. *Pest Manag Sci.* 2021;77(9):4084-4090. doi:10.1002/ps.6433.
 80. Prokopy RJ, Roitberg BD, Averill AL. Chemical mediation of resource partitioning in insects. In: Bell WJ, Cardé RT, editors. *Chemical ecology of insects.* Chapman and Hall; 1984. p.301-330.
 81. Pyke B, Rice M, Sabine B, Zalucki MP. The push-pull strategy: behavioural control of *Heliothis*. *Aust Cotton Grower.* 1987;9(1):7-9.
 82. Raj N. Pheromone traps in pest management. *Agri Roots.* 2025;3(11):Article 0281.
 83. Rajashekhar M, Rajashekar B, Reddy TP, Chandrashekara KM, Vanisree K, Ramakrishna K, et al. Evaluation of farmers friendly IPM modules for the management of fall armyworm, *Spodoptera frugiperda* (J. E. Smith) in maize in the hot semiarid region of India. *Sci Rep.* 2024;14:7118. doi:10.1038/s41598-024-57860-y.
 84. Randlkofer B, Obermaier E, Hilker M, Meiners T. Vegetation complexity: the influence of plant species diversity and plant structures on plant chemical complexity and arthropods. *Basic Appl Ecol.* 2010;11:383-395.
 85. Raptopoulos D, Betsi PC, Manikas N, Borodina I, Konstantopoulou M. Mating disruption of *Helicoverpa armigera* (Lepidoptera: Noctuidae) using yeast-derived pheromones in cotton fields. *Insects.* 2025;16(5):523. doi:10.3390/insects16050523.

86. Reddy GVP, Guerrero A. New pheromones and insect control strategies. *Vitam Horm.* 2010;83:493-519. doi:10.1016/S0083-6729(10)83020-7.
87. Regnier FE, Law JH. Insect pheromones. *J Lipid Res.* 1968;9(5):541-551. doi:10.1016/S0022-2275(20)42699-9.
88. Rhainds M, Therrien P, Morneau L. Pheromone-based monitoring of spruce budworm (Lepidoptera: Tortricidae) larvae in relation to trap position. *J Econ Entomol.* 2016;109(2):717-723. doi:10.1093/jee/tov393.
89. Rust MK. Integrated pest management. In: Capinera JL, editor. *Encyclopedia of entomology*. Springer; 2004.
90. Saucke H, Balasus A, Finckh MR, Formowitz B, Schmidt R, Kratt A. Mating disruption of pea moth (*Cydia nigricana*) in organic peas. *Entomol Exp Appl.* 2014;150(3):199-207.
91. Schroder R, Hilker M. The relevance of background odor in resource location by insects: a behavioral approach. *BioScience.* 2008;58(4):308-316. doi:10.1641/B580406.
92. Seeley TD. The honey bee colony as a superorganism. *Am Sci.* 1989;77(6):546-553.
93. Shani A, Clearwater J. Evasion of mating disruption in *Ephestia cautella* (Walker) by increased pheromone production relative to that of undisrupted populations. *J Stored Prod Res.* 2001;37(3):237-252.
94. Sharma A, Sandhi RK, Reddy GVP. A review of interactions between insect biological control agents and semiochemicals. *Insects.* 2019;10(12):439. doi:10.3390/insects10120439.
95. Sharma RK, Khokhar Y, Singh S. Management of fruit flies (*Bactrocera* spp.) in guava (*Psidium guajava*) by pheromone traps. *Indian J Agric Sci.* 2022;92(1):14-17. doi:10.56093/ijas.v92i1.120821.
96. Shearer DA, Boch R. 2-Heptanone in the mandibular gland secretion of the honey-bee. *Nature.* 1965;206:530. doi:10.1038/206530a0.
97. Sillam-Dusses D, Hanus R, Gaillard J, Brunet A, Joly F. (Z)-dodec-3-en-1-ol, a novel termite trail pheromone identified after solid phase microextraction from *Macrotermes annandalei*. *J Insect Physiol.* 2001;47(4-5):445-453. doi:10.1016/S0022-1910(00)00135-9.
98. Tabuchi K, Moriya S, Mizutani N, Ito K. Recording the occurrence of the bean bug, *Riptortus clavatus* (Thunberg) (Heteroptera: Alydidae), using an automatic counting trap. *Jpn J Appl Entomol Zool.* 2006;50(2):123-129.
99. Tan KH, Nishida R. Mutual reproductive benefits between a wild orchid, *Bulbophyllum patens*, and *Bactrocera* fruit flies via a floral synomone. *J Chem Ecol.* 2000;26(2):533-546. doi:10.1023/A:1005477926244.
100. Tan KH, Nishida R. Synomone or kairomone? *Bulbophyllum apertum* (Orchidaceae) flower releases raspberry ketone to attract *Bactrocera* fruit flies. *J Chem Ecol.* 2005;31(3):509-519. doi:10.1007/s10886-005-2023-8.
101. Tan KH, Nishida R, Toong YC. *Bulbophyllum cheiri*'s floral synomone lures fruit flies to perform pollination. *J Chem Ecol.* 2002;28(6):1161-1172. doi:10.1023/A:1016277500007.
102. Tan KH, Tan LT, Nishida R. Floral phenylpropanoid cocktail and architecture of *Bulbophyllum vinaceum* orchid in attracting fruit flies for pollination. *J Chem Ecol.* 2006;32(11):2429-2441. doi:10.1007/s10886-006-9152-0.
103. Toledo J, Campos SE, Flores S, Liedo P, Barrera JF, Villaseñor A, et al. Horizontal transmission of *Beauveria bassiana* in *Anastrepha ludens* (Diptera: Tephritidae) under laboratory and field cage conditions. *J Econ Entomol.* 2007;100(2):291-297. doi:10.1093/jee/100.2.291.
104. Tompkins JM. Ecosystem services provided by native New Zealand plants in vineyards [doctoral dissertation]. Lincoln: Lincoln University; 2010.
105. Trematerra P. Advances in the use of pheromones for stored-product protection. *J Pest Sci.* 2012;85(3):285-299. doi:10.1007/s10340-011-0407-9.
106. Vander Meer RK. Trail pheromones in pest control. In: Vander Meer RK, Breed MD, Winston ML, Espelie KE, editors. *Pheromone communication in social insects: ants, wasps, bees, and termites*. Westview Press; 1996. p.111-127.
107. Vega FE, Goettel MS, Blackwell M, Chandler D, Jackson MA, Keller S, et al. Fungal entomopathogens: new insights on their ecology. *Fungal Ecol.* 2009;2(4):149-159. doi:10.1016/j.funeco.2009.05.001.
108. Verheggen FJ, Haubruge É, Mescher MC. Alarm pheromones: chemical signaling in response to danger. *Vitam Horm.* 2010;83:215-239.
109. Vilela EF, Della Lucia MT. *Feromônios de insetos: biologia, química e emprego no manejo de pragas*. 2nd ed. Holos Editora; 2001.
110. Weinzierl R, Henn T, Koehler PG, Tucker CL. Insect attractants and traps. University of Florida IFAS Extension; 2005.
111. Winston ML. *The biology of the honey bee*. Cambridge, MA: Harvard University Press; 1987.
112. Witzgall P, Kirsch P, Cork A. Sex pheromones and their impact on pest management. *J Chem Ecol.* 2010;36(1):80-100. doi:10.1007/s10886-009-9737-y.
113. Witzgall P, Stelinski L, Gut L, Thomson D. Codling moth management and chemical ecology. *Annu Rev Entomol.* 2008;53:503-522. doi:10.1146/annurev.ento.53.103106.093323.
114. Wood DL. The role of pheromones, kairomones, and allomones in the host selection and colonization behavior of bark beetles. *Annu Rev Entomol.* 1982;27:411-446.
115. Wyatt TD. *Pheromones and animal behaviour: communication by smell and taste*. Cambridge: Cambridge University Press; 2003.
116. Wyatt TD. *Pheromones and animal behavior: chemical signals and signatures*. 2nd ed. Cambridge: Cambridge University Press; 2014. doi:10.1017/CBO9781139030748.
117. Xiu C, Pan H, Zhang F, Luo Z, Bian L, Li Z, et al. Identification of aggregation pheromones released by the stick tea thrips (*Dendrothrips minowai*) larvae and their application for controlling thrips in tea plantations. *Pest Manag Sci.* 2024;80:2528-2538.
118. Yousef M, Aranda-Valera E, Quesada-Moraga E. [Title not provided]. *J Pest Sci.* 2018;91:227-235. doi:10.1007/s10340-017-0874-8.
119. Yusuf AA. Allomones in social insects. In: Starr CK, editor. *Encyclopedia of social insects*. Springer; 2021. p.27-29. doi:10.1007/978-3-030-28102-17.

120. Zamljen SA, Bohinc T, Trdan S. Mass trapping as a sustainable approach for Scarabaeidae pest management in crops and grasslands. *Agriculture*. 2025;15(23):2406. doi:10.3390/agriculture15232406.
121. Zavala JA, Patankar AG, Gase K, Hui D, Baldwin IT. Manipulation of endogenous trypsin proteinase inhibitor production in *Nicotiana attenuata* demonstrates their function as antiherbivore defenses. *Plant Physiol*. 2004;134(3):1181-1190.